State of California
The Resources Agency
Department of Water Resources

DRAFT REPORT
SP-G2: EFFECTS OF PROJECT OPERATIONS ON GEOMORPHIC PROCESSES DOWNSTREAM OF OROVILLE DAM

TASK 7 – HYDRAULIC AND SEDIMENT TRANSPORT MODELING WITH FLUVIAL-12

Oroville Facilities Relicensing
FERC Project No. 2100

MARCH 2004

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REPORT SUMMARY

The construction of Oroville Dam has altered the hydraulic, geomorphic, and sediment transport regimes of the Feather River. This study task is designed to identify and evaluate these ongoing and future effects on channel morphology and sediment transport in the Lower Feather River. This study task addressed the following:

1. Determine conditions and factors affecting historic sediment transport.
2. Select the most appropriate fluvial model.
3. Collect data and insert into model.
4. Calibrate model using sediment data and cross-sections and document assumptions.
5. Run model for 25 and 50 years to determine ongoing and future changes in stream geomorphology and sediment transport.

Many human induced factors have affected fluvial hydraulics and sediment transport in the Lower Feather River. These include hydraulic mining, land use changes in the upper watershed (timber harvesting, agriculture, urbanization), dredging, gravel mining, and dam building. The completion of several dams in the 50's and 60's cut off the sediment supply from the watershed above, and changed streamflow and sediment transport in the river below. These effects are described in the Task 1.2 report.

Sediment transport data were available from the U.S. Geological Survey (1978) for a short time period directly after the construction of project facilities. The average annual pre-dam sediment yield at the Feather River at Oroville gage was estimated to be 3,264 tons per day (1902-62). The post dam yield (1968-75) was estimated at 42.5 tons per day. More recent sediment data were not available. Cross-sections were also available, documenting channel changes that have occurred over a number of years. Some of these cross-sections have increased in cross-sectional area up to 400 percent from channel bed and bank erosion. The cross-sections were also used to assist in the calibration of the fluvial model.

The FLUVIAL-12 model was selected from a number of choices for the following reasons:

1. Ability to incorporate a variety of sediment transport equations.
2. Availability of expert consultation from Dr. Howard Chang, the model developer.
3. Capability of modeling bank erosion.
4. Ability to model differential changes across the entire channel boundary.
5. Ability to use HEC-2 input data.

Major items that require calibration include the roughness coefficient, sediment transport equation, and the bank erodibility factor. The model was run using a number of different sediment transport equations. The Engelund-Hansen equation was selected because the results most closely resembled sediment transport data measured by the

USGS (1974). The model was calibrated by comparing changes in surveyed cross-sections between 1972 and 1997, and by comparing observed and calculated water surface profiles. Hydrologic data from 1972 to 1997 was used for calibration. The model was then run to predict conditions 50 years in the future. Hydrologic data from 1997 to 2002, followed by 1967 to 2002, and 1967 to 1977, was used to model the 50 year changes.

Appendix A, Draft Final Report "Fluvial Modeling Study of Feather River Responses to Oroville Dam and Related Issues", by Dr. Howard Chang (February 2004), presents the results of the fluvial modeling. A summary of the findings are presented in Section 5 and 6 of this report.

The study results will be used by other studies to help assess the project's ongoing effects on downstream water quality, aquatic and riparian resources, and protection of private lands and public trust resources. The effects of proposed resource actions, such as flow modifications, spawning gravel enhancements, and side channel development, can be modeled to determine effectiveness prior to implementation.

The 50-year FLUVIAL-12 model run predicts the sediment yield for the next 50 years. The sediment inflow into the study reach is cut off by Oroville Dam. The amount of bed material load in the Feather River passing the Thermalito Outfall (Low Flow Reach) is modeled at 0.5 million tons, or about 10,000 tons per year, or 27 tons per day. This is about half of the yield calculated by the USGS between 1968 and 1975. The yield is primarily a result of channel erosion since bed material is trapped by Oroville Dam. Finer sediments are more easily removed from the channel boundary, leaving the coarser sediment behind. The selective sediment transport has resulted in the gradual coarsening and armoring of the bed material.

The pattern of sediment delivery shows a sharp rise in delivery in the High Flow Reach just below the Thermalito Afterbay confluence. This is related to the increase in flow from Thermalito Afterbay and therefore an increase in erosion from the channel boundary. The net bed material yield is about 2.6 million tons after 50 years. Of this quantity, about 2.1 million tons was from bed erosion in the reach over the 50 years. The remaining 0.5 million tons was introduced load from the Low Flow Reach.

The model run shows a large increase in the sediment size after 50 years. The largest increase in size was directly below the Fish Barrier Dam, with a D50 increase from 120 mm to 150 mm and at River Mile 56, with an increase from 60mm to 110mm.

Channel geometry changes occur due to scour and fill, which is not generally uniformly distributed across the channel width. Scour of the bed may be accompanied by scour or fill in the overbank area, or vice versa. These changes in channel morphology in turn directly affect the hydraulics of flow and sediment transport.

Changes in channel geometry are depicted by changes in thalweg profile and changes in channel cross-section. Modeled water surface and channel thalweg profiles show that channel bed degradation is predicted at most cross-sections, with aggradation at some locations. The channel degradation is consistent with the continued erosion. Future changes are limited by bed armoring, which in turn, will reduce future bed erosion and sediment yield.

Those reaches near mining areas are subject to greater changes than other areas. This is because of the disruption in channel profile and cross-section, resulting in sediment deposition within the mining areas and scour in the areas above and below.

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1.0 INTRODUCTION

The purpose of this report is to evaluate fluvial, sediment transport, and geomorphic changes in the Lower Feather River resulting from human induced changes and the construction of Oroville Dam. This study is primarily focused on the Feather River between the Fish Barrier Dam and the town of Gridley. The report consists of evaluating past changes and predicting future changes.

The first part of the study evaluates existing sediment, bed material, and channel morphology data. The second part uses predictive mathematical modeling.

Sediment transport data were available from the U.S. Geological Survey (1978) for a short time period directly after the construction of project facilities. More recent sediment data were not available. Cross-sections were also available, documenting channel changes that have occurred over a number of years. These were used to assist in the calibration of the fluvial model. Some data were available in regards to human induced changes in the sediment supply. These include historic accounts of hydraulic mining, timber harvesting, urbanization, dam building, dredging, gravel mining, and others. Particularly useful were maps, charts, cross-sections, and aerial photographs showing river conditions at various times during the last 100 years.

The FLUVIAL-12 model was selected to predict future changes. It will be used to identify the hydraulic, geomorphic, and sediment transport changes that have occurred since dam closure in 1967, and to predict future changes. The modeling results will be used to determine Oroville Dam effects on spawning riffles, flooding, and riparian habitat. Based on the results of the study, the model will be used to determine the need for protection, mitigation or enhancement measures. The study results will also be used by other studies to help assess the project's ongoing effects on downstream water quality, aquatic and riparian resources, and protection of private lands and public trust resources.

1.1 BACKGROUND INFORMATION

The two main branches of the Feather, the North Fork and the Middle Fork, drain the Sierra Nevadas to the East. They join with each other and the smaller West Branch and South Fork in the 3.5 million acre-foot Lake Oroville, near the town of Oroville, California. Downstream from the lake, the combined tributaries of the Feather River flow into the flat valley floor of the Sacramento Valley. The river then flows southerly about 70 miles to the Sacramento River at Verona.

Oroville Dam is about 5.5 miles upstream from the town of Oroville. The dam is an earthfill structure, consisting of an inclined impervious gravel-clay core founded on a concrete core block, with sand-gravel-cobble transitions and shells both upstream and downstream. Construction began on the embankment in July 1962, and the last feature of the dam, the concrete spillway, was completed in May 1968. Storage began in November 1967, although some attenuation of flood peaks occurred before then, most notably during the December 1964 flood. The lake capacity is about 3.5 million acre-feet.

The Lower Feather River may be divided into several hydrologic reaches. The Low Flow Reach begins below the Diversion Dam at River Mile 67 and ends at the Thermalito Afterbay Outfall to the Feather River at RM 59. Streamflow on the Feather River is gaged at the Oroville stream gage. The flow is held at a minimum of 600 cubic feet per second for most of the year.

Most of the release from the Oroville Reservoir is diverted by the Thermalito Diversion Dam into the Thermalito Forebay and Afterbay. The High Flow Reach begins below the Afterbay where water is again released to the Feather River. Releases can vary from zero to about 23,000 cfs. Flood flows above this value, spill into the Feather at the upper end of the Low Flow Reach and affect both the low and high flow reaches. The Yuba River enters the Feather at RM 28 and the Bear River at RM 7. The combined flow of all three rivers is measured on the Feather River near the city of Nicolaus (Nicolaus gage). The hydrology is described in detail in the Task 1.2 report.

1.1.1 Human Induced Changes

Streams change their sediment transport with time, typically in response to changes in climate, geologic events, changes in base level, and other factors. The Feather River today is also changing, but mostly in response to human activity. These activities include past land use in the upper watershed, hydraulic mining, water diversions, and dam construction. These activities have resulted in large changes in water and sediment yields to the lower Feather River. Hydraulic mining introduced massive volumes of sediment into the stream system between the 1850s and 1890s. Timber harvesting and agriculture changed the vegetation and generally increased both water and sediment yields. Later, numerous dams were constructed in the upper watershed, trapping sediment and altering streamflow.

Beginning in 1967, regulation of the lower Feather River by the Oroville Facilities contributed to streamflow and sediment discharge changes.

Downstream, the river is affected by the streamflow amount and altered distribution pattern, both instrumental in channel formation. These include attenuation of peak flows, decreased winter flows, increased summer flows, and changes the historic flow frequencies.

The larger flows, occurring only a small percentage of the time, transport most of the sediment because suspended sediment transport increases at a rate of about the square of streamflow, and bed material increases as the cube of velocity. Since sediment and streamflow are the primary factors influencing geomorphology, channel changes will occur as the river adjusts to these modified conditions.

The Feather River is an important resource for salmonid spawning habitat in California, second only to the Sacramento River. The completion of Oroville Dam in 1967 resulted in further reduction of this habitat adding to the impacts from the earlier PG&E projects. This impact was mitigated by the Feather River Fish Hatchery. This Hatchery provides an artificial spawning and rearing facility for Steelhead and Chinook salmon, although many Chinook salmon still spawn naturally below the dam.

The Oroville Facilities also contributed changes that affect hydrology and sediment transport characteristics, altering the movement of water, sediment, and woody debris down the river. This results in an altered hydrologic regime that includes changes to the yearly, monthly, and daily stream flow distributions; bankfull discharge, flow exceedance, and peak flow.

The reservoir contributes to the capture of sediment eroded from the watershed. This changes downriver patterns of sediment transport, deposition, scour, mobilization of sediment, and turbidity levels. All of these can result in the coarsening of spawning gravel on riffles, which in turn may adversely affect Chinook salmon and steelhead.

These changes to the river hydrology and sedimentation patterns will in turn alter the channel morphology. These can include changes to the channel shape, stability and capacity.

1.1.2 Other Studies

Studies related to spawning gravel quantity and quality began before construction of Oroville Dam. DWR (1965) studied pre-dam channel characteristics, and then DWR (1969) and the USGS (1972) conducted studies to document channel changes. In 1977 DFG studied the interim impacts of the dam on salmonid escapement. In 1978, the USGS did another study to evaluate sediment transport and discharge. Because of the findings of several of the previous investigations, DWR (1982) prepared the Feather River Spawning Gravel Baseline Study to determine the condition of spawning gravel in the upper Feather River. The report identified factors resulting in the reduction of spawning gravel quality. These include the loss of gravel recruitment from areas above Oroville Dam and the effect of scouring flood flows. A follow-up habitat restoration project was conducted by DWR and DFG in 1982 at the riffle sites adjacent to the Hatchery. These sites were identified in the baseline study as having undergone significant post-dam degradation.

Surface and bulk gravel sampling for the 1982 study showed that riffles in the river between the Oroville Fish Hatchery and the Highway 70 Bridge are paved by cobbles. The degree of armoring diminishes downstream. Below the Highway 162 Bridge the armoring effect diminishes rapidly and the gravel in riffles is generally appropriate for salmon spawning.

In the 1982 study, surface samples were taken on point bars and the size distribution, median, first and second standard deviation, skewness and kurtosis calculated. One hundred and seventy six surface samples were taken between the Fish Barrier Dam and Honcut Creek. Bulk samples were taken on 18 point bars.

Although the study concluded that in-channel enhancement projects would run a high risk of failure because of high velocities, lack of recruitment, and short flood recurrence intervals, it also proposed a comprehensive management and monitoring program that included restoration and enhancement of habitat.

Channel cross-sections surveyed by the USACE between 1909 and 1911 were resurveyed by the DWR in 1965 and 1969, and then again in 2002 and 2003. These sections show net scour, both widening and deepening. This trend is still continuing, as shown by surveys done by DWR in 2002 and 2003. Descriptions of these sections are in the Task 5 Report.

There are no current sediment transport measurements available on Feather River. The FLUVIAL-12 program develops long-term bed material yields based on sediment transport equations, but these are not actual measurements.

The USGS (1978) report “Sediment Transport in the Feather River, Lake Oroville to Yuba City, California” is the most recent source of sediment transport measurements. The USGS compiled and measured (1965-75) suspended sediment discharge at the following stations: Feather River at Oroville; Feather River near Gridley; and the Feather River at Yuba City. No other sediment data was found on either the USGS or DWR websites.

1.1.3 Study Area Location and Access

The study reach is the 67-mile reach from the Fish Barrier Dam downriver of Oroville Dam to the confluence with the Sacramento River at Verona (Figure 1.1-1). Verona is assumed to be the downstream extent of observable effects of flow modification. The study area extends laterally to the 500-year floodplain boundary as defined by the USACE (1997).

The study area is further divided into three river reaches based on differences in the hydrologic flow regime. The Low Flow Reach is the 8-mile stretch between the Fish Diversion Dam and the Thermalito Afterbay outflow. The High Flow Reach is the 31-mile stretch between the Afterbay outflow and the Yuba River. The third is the Below Yuba River Reach, the 28-mile stretch between the Yuba and the confluence with the Sacramento River. The length of stream modeled using FLUVIAL-12 includes the Low

Flow Reach and the High Flow Reach downstream to the confluence of Honcut Creek at RM 44.

The river is accessible by vehicles in a number of places. Public boat ramps are also available. Access to the Low Flow Reach is by a public ramp on the left bank at River Run Park and the right bank just upriver of the Thermalito Afterbay outflow. Access to the High Flow Reach is also supported by the ramp just upriver of the Thermalito Afterbay outflow and a second ramp on the right bank just east of the town of Live Oak. Jet boats can often be used in the High Flow Reach and sometimes in the Low Flow Reach dependent on flow. Seasonal variations in flow can often make some riffles difficult or impossible to navigate and submerged snags can be an additional hazard.

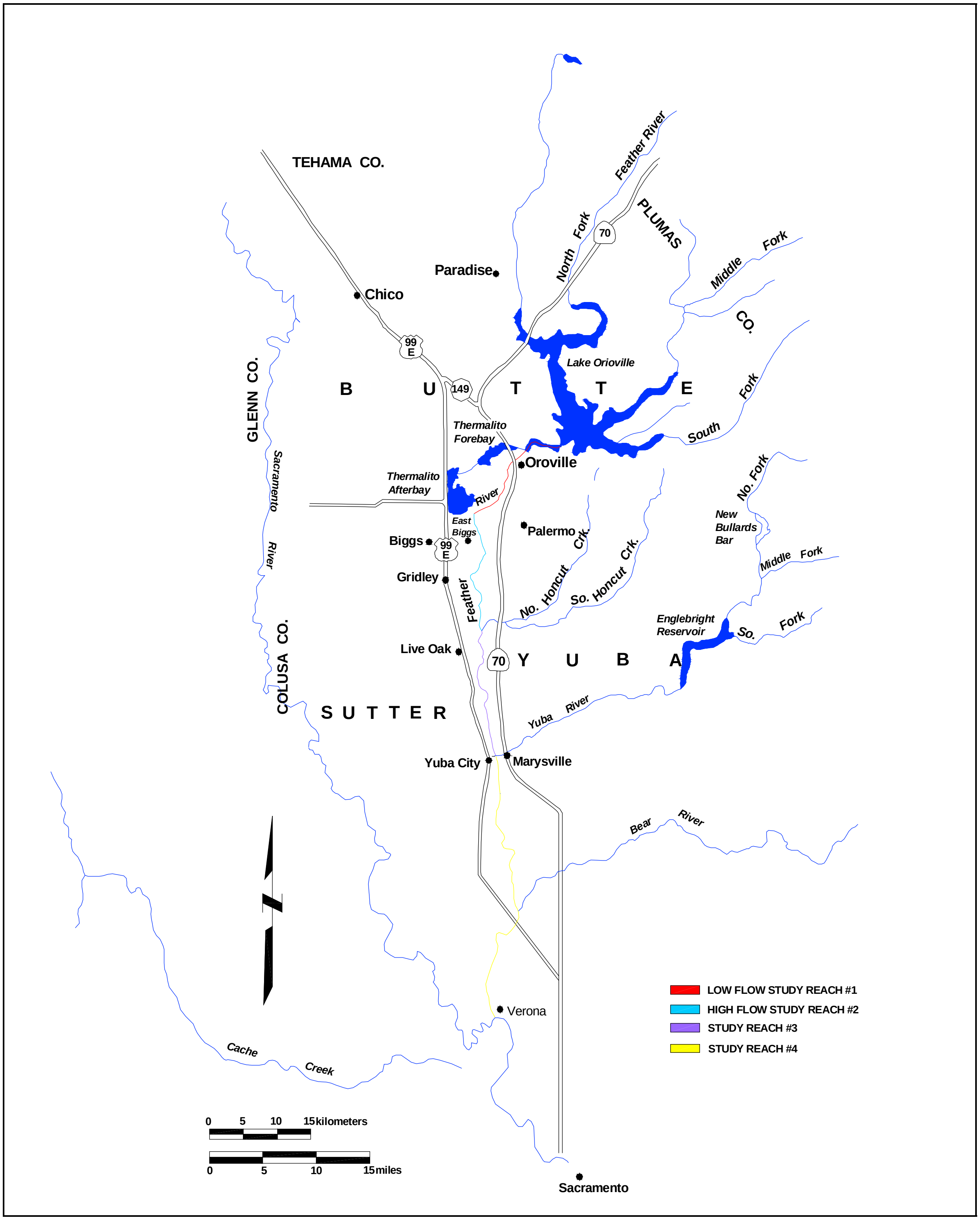

Figure 1.1-1. SP-G2 Geomorphic Study Area and Subreaches, Lake Oroville to Verona

1.2 DESCRIPTION OF FACILITIES

The Oroville Facilities were developed as part of the State Water Project, a water storage and delivery system of reservoirs, aqueducts, power plants, and pumping plants. The main purpose of the SWP is to store and distribute water to supplement the needs of urban and agricultural water users in northern California, the San Francisco Bay area, the San Joaquin Valley, and southern California. The Oroville Facilities are also operated for flood management, power generation, to improve water quality in the Delta, provide recreation, and enhance fish and wildlife.

FERC Project No. 2100 encompasses 41,100 acres and includes Oroville Dam and Reservoir, three power plants (Hyatt Pumping-Generating Plant, Thermalito Diversion Dam Power Plant, and Thermalito Pumping-Generating Plant), Thermalito Diversion Dam, the Feather River Fish Hatchery and Fish Barrier Dam, Thermalito Power Canal, Oroville Wildlife Area, Thermalito Forebay and Forebay Dam, Thermalito Afterbay and Afterbay Dam, and transmission lines, as well as a number of recreational facilities. An overview of these facilities is provided on Figure 1.2-1. The Oroville Dam, along with two small saddle dams, impounds Lake Oroville, a 3.5-million-acre-feet (maf) capacity storage reservoir with a surface area of 15,810 acres at its normal maximum operating level.

The hydroelectric facilities have a combined licensed generating capacity of approximately 762 megawatts (MW). The Hyatt Pumping-Generating Plant is the largest of the three power plants with a capacity of 645 MW. Water from the six-unit underground power plant (three conventional generating and three pumping-generating units) is discharged through two tunnels into the Feather River just downstream of Oroville Dam. The plant has a generating and pumping flow capacity of 16,950 cfs and 5,610 cfs, respectively. Other generation facilities include the 3-MW Thermalito Diversion Dam Power Plant and the 114-MW Thermalito Pumping-Generating Plant.

Thermalito Diversion Dam four miles downstream of the Oroville Dam creates a tail water pool for the Hyatt Pumping-Generating Plant and is used to divert water to the Thermalito Power Canal. The Thermalito Diversion Dam Power Plant is a 3-MW power plant located on the left abutment of the Diversion Dam. The power plant releases a maximum of 615 cubic feet per second (cfs) of water into the river.

The Power Canal is a 10,000-foot-long channel designed to convey generating flows of 16,900 cfs to the Thermalito Forebay and pump-back flows to the Hyatt Pumping-Generating Plant. The Thermalito Forebay is an off-stream regulating reservoir for the 114-MW Thermalito Pumping-Generating Plant. The Thermalito Pumping-Generating Plant is designed to operate in tandem with the Hyatt Pumping-Generating Plant and has generating and pump-back flow capacities of 17,400 cfs and 9,120 cfs, respectively. When in generating mode, the Thermalito Pumping-Generating Plant discharges into the Thermalito Afterbay, which is contained by a 42,000-foot-long earth-fill dam. The

Afterbay is used to release water into the Feather River downstream of the Oroville Facilities, helps regulate the power system, provides storage for pump-back operations, and provides recreational opportunities. Several local irrigation districts receive water from the Afterbay.

The Feather River Fish Barrier Dam is downstream of the Thermalito Diversion Dam and immediately upstream of the Feather River Fish Hatchery. The flow over the dam maintains fish habitat in the low-flow channel of the Feather River between the dam and the Afterbay outlet, and provides attraction flow for the hatchery. The hatchery was intended to compensate for spawning grounds lost to returning salmon and steelhead trout from the construction of Oroville Dam. The hatchery can accommodate 15,000 to 20,000 adult fish annually.

The Oroville Facilities support a wide variety of recreational opportunities. They include: boating (several types), fishing (several types), fully developed and primitive camping (including boat-in and floating sites), picnicking, swimming, horseback riding, hiking, off-road bicycle riding, wildlife watching, hunting, and visitor information sites with cultural and informational displays about the developed facilities and the natural environment. There are major recreation facilities at Loafer Creek, Bidwell Canyon, the Spillway, North and South Thermalito Forebay, and Lime Saddle. Lake Oroville has two full-service marinas, five car-top boat launch ramps, ten floating campsites, and seven dispersed floating toilets. There are also recreation facilities at the Visitor Center and the OWA.

The OWA comprises approximately 11,000-acres west of Oroville that is managed for wildlife habitat and recreational activities. It includes the Thermalito Afterbay and surrounding lands (approximately 6,000 acres) along with 5,000 acres adjoining the Feather River. The 5,000 acre area straddles 12 miles of the Feather River, which includes willow and cottonwood lined ponds, islands, and channels. Recreation areas include dispersed recreation (hunting, fishing, and bird watching), plus recreation at developed sites, including Monument Hill day use area, model airplane grounds, three boat launches on the Afterbay and two on the river, and two primitive camping areas. California Department of Fish and Game's habitat enhancement program includes a wood duck nest-box program and dry land farming for nesting cover and improved wildlife forage. Limited gravel extraction also occurs in a number of locations.

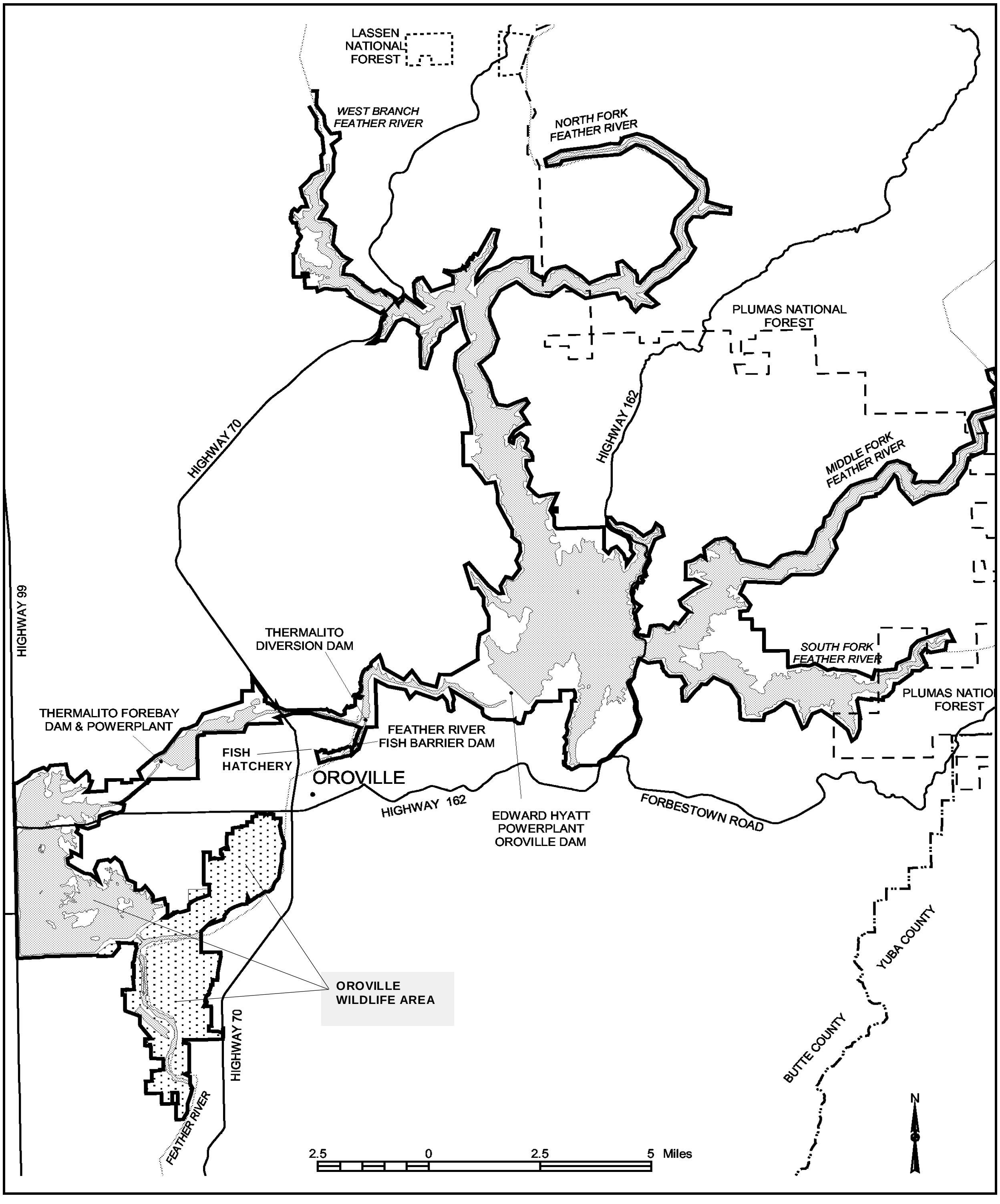

Figure 1.2-1. Oroville Facilities FERC Project Boundary

1.3 CURRENT OPERATIONAL CONSTRAINTS

Operation of the Oroville Facilities varies seasonally, weekly and hourly, depending on hydrology and the objectives the Department of Water Resources is trying to meet. Typically, releases to the Feather River are managed to conserve water while meeting a variety of water delivery requirements, including flow, temperature, fisheries, recreation, diversion and water quality. Lake Oroville stores winter and spring runoff for release to the Feather River as necessary for project purposes. Meeting the water supply objectives of the SWP has always been the primary consideration for determining Oroville Facilities operation (within the regulatory constraints specified for flood control, in-stream fisheries, and downstream uses). Power production is scheduled within the boundaries specified by the water operations criteria noted above. Annual operations planning are conducted for multi-year carry over. The current methodology is to retain half of the Lake Oroville storage above a specific level for subsequent years. Currently, that level has been established at 1,000,000 acre-feet (af); however, this does not limit draw down of the reservoir below that level. If hydrologic conditions are drier than expected or requirements greater than expected, additional water would be released from Lake Oroville. The operations plan is updated regularly to reflect changes in hydrology and downstream operations. Typically, Lake Oroville is filled to its maximum annual level of up to 900 feet above mean sea level (msl) in June and then can be lowered as necessary to meet downstream requirements, to its minimum level in December or January. During drier years, the lake may be drawn down more and may not fill to the desired levels the following spring. Project operations are directly constrained by downstream operational constraints and flood management criteria as described below.

1.3.1 Downstream Operation

An August 1983 agreement between DWR and DFG entitled, “Agreement Concerning the Operation of the Oroville Division of the State Water Project for Management of Fish & Wildlife,” sets criteria and objectives for flow and temperatures in the low flow channel and the reach of the Feather River between Thermalito Afterbay and Verona. This agreement: (1) establishes minimum flows between Thermalito Afterbay Outlet and Verona which vary by water year type; (2) requires flow changes under 2,500 cfs to be reduced by no more than 200 cfs during any 24-hour period, except for flood management, failures, etc.; (3) requires flow stability during the peak of the fall-run Chinook spawning season; and (4) sets an objective of suitable temperature conditions during the fall months for salmon and during the later spring/summer for shad and striped bass.

1.3.1.1 Instream Flow Requirements

The Oroville Facilities are operated to meet minimum flows in the Lower Feather River as established by the 1983 agreement (see above). The agreement specifies that Oroville Facilities release a minimum of 600 cfs into the Feather River from the Thermalito Diversion Dam for fisheries purposes. This is the total volume of flows from the diversion dam outlet, diversion dam power plant, and the Feather River Fish Hatchery pipeline.

Generally, the instream flow requirements below Thermalito Afterbay are 1,700 cfs from October through March, and 1,000 cfs from April through September. However, if runoff for the previous April through July period is less than 1,942,000 af (i.e., the 1911-1960 mean unimpaired runoff near Oroville), the minimum flow can be reduced to 1,200 cfs from October to February, and 1,000 cfs for March. A maximum flow of 2,500 cfs is maintained from October 15 through November 30 to prevent spawning in overbank areas that might become de-watered.

1.3.1.2 Temperature Requirements

The Diversion Pool provides the water supply for the Feather River Fish Hatchery. The hatchery objectives are 52°F for September, 51°F for October and November, 55°F for December through March, 51°F for April through May 15, 55°F for last half of May, 56°F for June 1-15, 60°F for June 16 through August 15, and 58°F for August 16-31. A temperature range of plus or minus 4°F is allowed for objectives, April through November.

There are several temperature objectives for the Feather River downstream of the Afterbay Outlet. During the fall months, after September 15, the temperatures must be suitable for fall-run Chinook. From May through August, they must be suitable for shad, striped bass, and other warmwater fish.

The National Marine Fisheries Service has also established an explicit criterion for steelhead trout and spring-run Chinook salmon. Memorialized in a biological opinion on the effects of the Central Valley Project and SWP on Central Valley spring-run Chinook and steelhead as a reasonable and prudent measure; DWR is required to control water temperature at Feather River mile 61.6 (Robinson's Riffle in the low-flow channel) from June 1 through September 30. This measure requires water temperatures less than or equal to 65°F on a daily average. The requirement is not intended to preclude pump-back operations at the Oroville Facilities needed to assist the State of California with supplying energy during periods when the California ISO anticipates a Stage 2 or higher alert.

The hatchery and river water temperature objectives sometimes conflict with temperatures desired by agricultural diverters. Under existing agreements, DWR provides water for the Feather River Service Area contractors. The contractors claim a need for warmer water during spring and summer for rice germination and growth (i.e., 65°F from approximately April through mid May, and 59°F during the remainder of the growing season). There is no obligation for DWR to meet the rice water temperature goals. However, to the extent practical, DWR does use its operational flexibility to accommodate the FRSA contractor's temperature goals.

1.3.1.3 Water Diversions

Monthly irrigation diversions of up to 190,000 (July 2002) af are made from the Thermalito Complex during the May through August irrigation season. Total annual entitlement of the Butte and Sutter County agricultural users is approximately 1 maf. After meeting these local demands, flows into the lower Feather River continue into the Sacramento River and into the Sacramento-San Joaquin Delta. In the northwestern portion of the Delta, water is pumped into the North Bay Aqueduct. In the south Delta, water is diverted into Clifton Court Forebay where the water is stored until it is pumped into the California Aqueduct.

1.3.1.4 Water Quality

Flows through the Delta are maintained to meet Bay-Delta water quality standards arising from DWR's water rights permits. These standards are designed to meet several water quality objectives such as salinity, Delta outflow, river flows, and export limits. The purpose of these objectives is to attain the highest water quality, which is reasonable, considering all demands being made on the Bay-Delta waters. In particular, they protect a wide range of fish and wildlife including Chinook salmon, Delta smelt, striped bass, and the habitat of estuarine-dependent species.

1.3.2 Flood Management

The Oroville Facilities are an integral component of the flood management system for the Sacramento Valley. During the wintertime, the Oroville Facilities are operated under flood control requirements specified by the U.S. Army Corps of Engineers (USACE). Under these requirements, Lake Oroville is operated to maintain up to 750,000 af of storage space to allow for the capture of significant inflows. Flood control releases are based on the release schedule in the flood control diagram or the emergency spillway release diagram prepared by the USACE, whichever requires the greater release. Decisions regarding such releases are made in consultation with the USACE.

The flood control requirements are designed for multiple use of reservoir space. During times when flood management space is not required to accomplish flood management objectives, the reservoir space can be used for storing water. From October through March, the maximum allowable storage limit (point at which specific flood release would have to be made) varies from about 2.8 to 3.2 maf to ensure adequate space in Lake

Oroville to handle flood flows. The actual encroachment demarcation is based on a wetness index, computed from accumulated basin precipitation. This allows higher levels in the reservoir when the prevailing hydrology is dry while maintaining adequate flood protection. When the wetness index is high in the basin (i.e., wetness in the watershed above Lake Oroville), the flood management space required is at its greatest amount to provide the necessary flood protection. From April through June, the maximum allowable storage limit is increased as the flooding potential decreases, which allows capture of the higher spring flows for use later in the year. During September, the maximum allowable storage decreases again to prepare for the next flood season. During flood events, actual storage may encroach into the flood reservation zone to prevent or minimize downstream flooding along the Feather River.

2.0 NEED FOR STUDY

The Environmental Work Group identified changes in sediment transport and geomorphology caused by the Oroville Facilities operations as potential impacts on the fluvial and riparian ecosystem.

2.1 PURPOSE AND SCOPE

A naturally functioning channel in dynamic equilibrium is capable of transporting the water and sediment delivered to it without significantly changing its geometry, streambed composition, or gradient through time. The flow conditions that promote this stability can be described as geomorphically significant flows (bankfull). These flows do the majority of the sediment transport and are considered most responsible for channel form. A natural flow regime typically includes flow ranges responsible for in-channel flushing or over bank flows to support riparian vegetation, along with channel-forming flows.

The altered sediment routing and hydrology caused by the Oroville Facilities have affected river morphology. There is a need to understand these relationships and identify potential protection, mitigation and enhancement measures.

The geomorphic investigation will compare historic and current conditions to help identify ongoing project effects to the downstream reach defined in this study. This information will be used to identify continuing project effects to downstream geomorphologic processes. It will also be used by other studies to help assess the project's effects on plant, fish, animal, and riparian resources caused by hydrologic, channel, and sediment routing changes. These data, together with other study results, will provide boundary conditions for assessing potential Resource Actions.

3.0 STUDY OBJECTIVES

3.1 APPLICATION OF STUDY INFORMATION

The objective is to determine the ongoing effects of altered downstream hydrology and sediment retention in Lake Oroville on channel morphology and sediment transport below Lake Oroville. The study results will also be used to help assess the project's potential ongoing effects on downstream water quality, aquatic and riparian resources, private lands and public trust resources.

4.0 METHODOLOGY

4.1 STUDY DESIGN

The original seven individual tasks and sub-tasks specified in the SP-G2 study plan have been re-organized into the following reports:

- Task 1.1 - obtain, review, and summarize existing resource data and references.
- Task 1.2 – prepare a general description of the lower Feather River and watershed.
- Task 2 - map and characterize spawning riffles.
- Task 3 - evaluate changes to the channel morphology by re-establishing historic cross-section surveys and photo points.
- Tasks 4, 6 - assess current channel characteristics and monitor selected cross-sections for significant changes to those characteristics; establish bank erosion monitoring sites.
- Task 5 - determine project effects on river hydraulic and geomorphic parameters.
- Task 7 - model channel hydraulics and sediment transport and make predictions for future project related changes.

Each of these bulleted items is a separate report. This specific report is organized by and fulfills the requirements for Task 7.

4.2 HOW AND WHERE THE STUDIES WERE CONDUCTED

Work began on Task 7 in June, 2002. Office work has focused on researching and collecting references and data sets, performing sieve analyses of sediment samples, documenting field surveys, and preparation of maps, charts, and figures. The work has been geared to providing data for development of the FLUVIAL-12 sediment transport model. This ongoing work includes weekly coordination with Engineering staff and Dr. Howard Chang, the model developer and consultant. Field work has concentrated on finding and re-surveying historic cross-sections, developing hydrologic data, and collecting bulk sediment samples. Most of the data used in the modeling are reported in detail in other task reports.

Model development, calibration, and results were done by Dr. Howard Chang, consultant, and reported in Task 7, Appendix A.

5.0 STUDY RESULTS

The first part of the study consisted of evaluating pre-existing sediment transport data, historic cross-sections, and bed material sampling data. The second part consisted of developing and calibrating a FLUVIAL-12 sediment transport model to predict ongoing and future changes that will occur in 50 years.

5.1 EVALUATION OF EXISTING SEDIMENT DATA

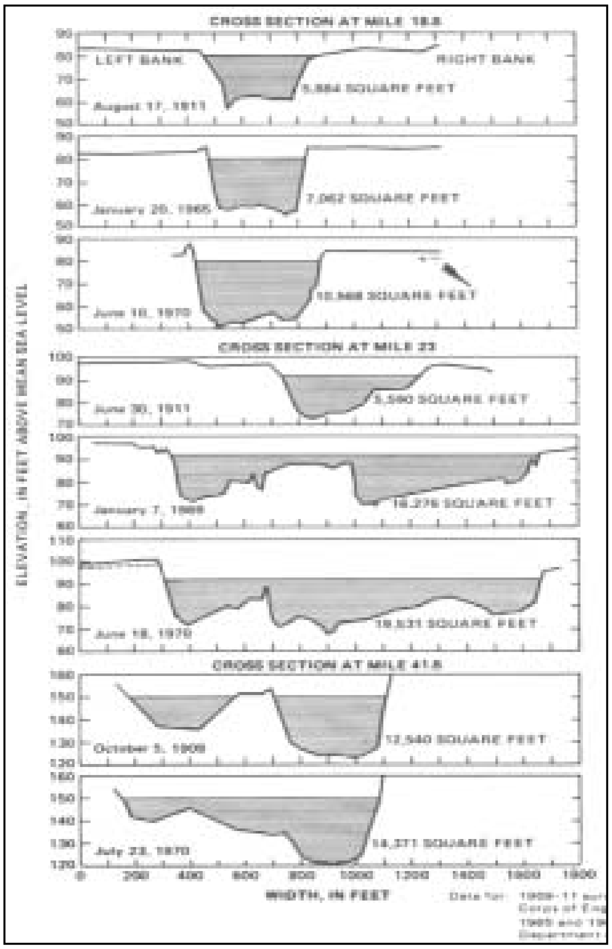

Figure 5.1-1. Feather River Cross-section Changes at RM 46.5, RM 51, and RM 69 from 1909 to 1970. (USGS 1978)

Channel cross-sections surveyed by the USACE between 1909 and 1911 were resurveyed by the DWR in 1965 and 1969, and then again in 2002 and 2003. These sections show net channel scour, both widening and deepening. This trend is still continuing, as shown by surveys done by DWR in 2002 and 2003. Descriptions of these sections are in the Task 5 report.

There are no current sediment transport measurements available on Feather River. The FLUVIAL-12 program develops long-term bedload yields based on sediment transport equations, but these are not actual measurements.

The USGS (1978) report "Sediment Transport in the Feather River, Lake Oroville to Yuba City, California" is the most recent. The USGS compiled and measured (1965-75) suspended sediment discharge at the following stations: Feather River at Oroville; Feather River near Gridley; and the Feather River at Yuba City. No other sediment data was found on either the USGS or DWR websites.

Figure 5.1-1 shows changes in selected channel cross-sections between 1909 and 1970. During this time, the cross-sectional areas increased from 17% at some cross-sections to almost 400% at others. This increase in channel area is a direct result of the post hydraulic mining era, when hydraulic mining debris was washing out of the system. The post mining degradation trend makes it more difficult to determine the additional effect of project facilities.

5.1.1 Feather River At Oroville Sediment Transport

According to the USGS (1978), an estimated average total sediment discharge of 3,750 tons is trapped daily by the dam. This was the amount of material historically (1902-62) discharged to the downstream channel. Of this amount, the USGS estimates that about 3,264 (87%) was suspended and 485 (13%) was unsampled load (bedload). Note that this is not the true sediment yield of the watershed, since numerous dams were constructed on various tributaries during this time period.

A total sediment input (bedload and suspended load) of about 3,750 tons per day into Lake Oroville suggests that a sediment deficit of about 50 million tons to the Feather River below the dam has occurred between 1967 and the present.

The USGS (1978) estimated the pre-dam daily mean discharge as 5,790 cfs and the total suspended sediment yield as 72,720,000 tons (1902-1962). The computation of pre-dam suspended sediment discharge by the USGS is shown in Table 5.1-1.

Table 5.1-1. Sediment Data from Lower Feather River Gaging Stations (from USGS 1978).

Station			Period of Record		Water discharge (ft^3/s)			Suspended-sediment discharge				
Number	Name	Location	Water years	# of years	Max day	Min day	Daily mean	Max day (tons)	Min day tons)	Daily mean: Tons	Daily mean: Ton/mi² [1]	Average water-weighted concentration (mg/L)
11407000	Feather River at Oroville	Lat 39°31'18"	1902-67	66	187,000	577	5,834					
		Long 121° 32'48"	1902-62	61	187,000	577	5,790			3,264 [2]	1.083 [2]	209 [2]
			1957-62 [3]	6	95,800	842	4,918	365,000	3.0	1,142	0.379	86
			1965-67	3	156,000	704	6,921	711,000	7.6	3,669	1.217	196
			1968-75	8	533,000	222	1,062	7,660	0.6	42.5	2.50	15
			1974-75	2	37,300	369	1,213	1,110	1.1	23.6	1.39	7
11407150	Feather River near Gridley	Lat 39°22'00"	1965-67	3	149,000	117	5,970	409,000	1.4	3,355	1.094	208
		Long 121°38'46"	1968-75	8	71,800	366	5,521	42,100	2.4	280	4.1	19
			1974-75	2	54,000	1,100	7,438	3,930	21	278	4.0	14
11407700	Feather River at Yuba City	Lat 39°08'20"	1965-67	3	156,000	166	6,325	334,000	12	3,806	1.131	223
		Long 121°36'17"	1968-75	8	74,500	410	5,889	54,100	18	1,815	4.95	114
			1974-75	2	55,300	1,250	7,905	35,800	56	2,432	6.63	114

[1] After 1968 the effective drainage area is assumed to be equal to the area downstream from Oroville Dam.
[2] Estimated.
[3] Does not include October 1956.

The estimated daily mean suspended-sediment discharge was derived by sampling suspended sediment at a variety of discharges during the period 1957-67. A rating table was developed that was then applied to the 1902-62 time period. Note that sediment estimates derived in this manner are approximate.

Post dam sediment sampling between 1968 and 1975 resulted in an estimated suspended sediment yield of 42.5 tons per day, demonstrating a dramatic shift between pre- and post dam yield.

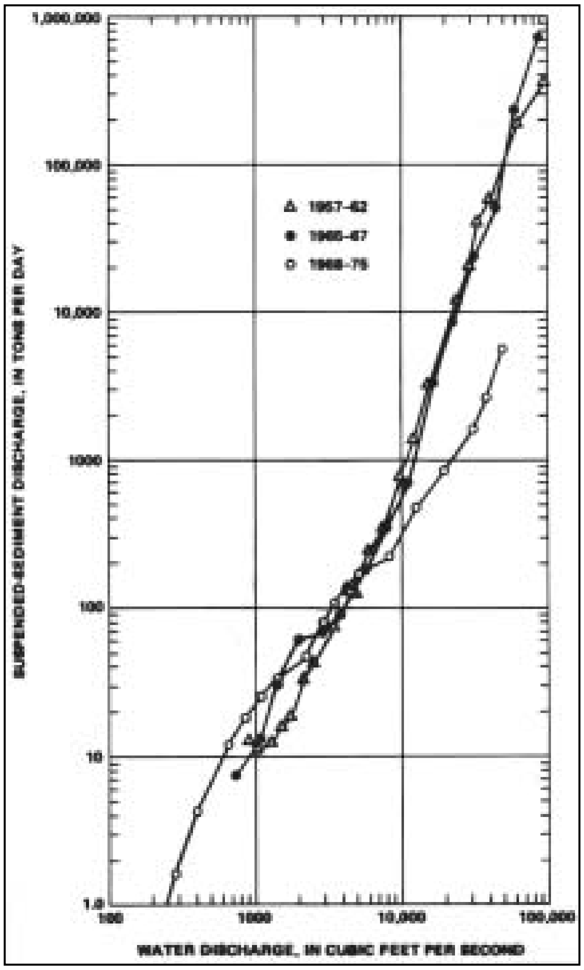

Figure 5.1-2. Relation between Streamflow and Suspended Sediment Discharge, Feather River at Oroville.

Figure 5.1-2 shows the relation between streamflow and suspended sediment discharge for the pre-dam years 1957-1962 and1965-1967, and the post dam years 1968-1975. The two pre-dam curves show that the amount of sediment can change significantly from year to year. This is generally in response to major flood events, one that occurred in December 1964 (1965 water year). The post dam curve (1968-75) demonstrates a large drop in suspended sediment discharge for the higher flows that carry most of the sediment. For example a pre-dam flow of 60,000 cfs would transport about 80,000 tons per day. The same post dam flow would transport only 7,000 tons per day.

Figure 5.1-3 shows the suspended sediment concentration frequency curves for the Oroville gage. Post dam flows with a 1% or smaller recurrence interval carried more than one order of magnitude less sediment concentration than the same pre-dam flows.

5.1.2 Feather River Near Gridley Sediment Transport

This gage (USGS 11407150) has a short period of record and has been discontinued. Table 5.1-1, in the previous section, shows the suspended sediment discharge for the pre-dam 1965-67, and post-dam 1968-75 hydrologic periods. The USGS estimated the

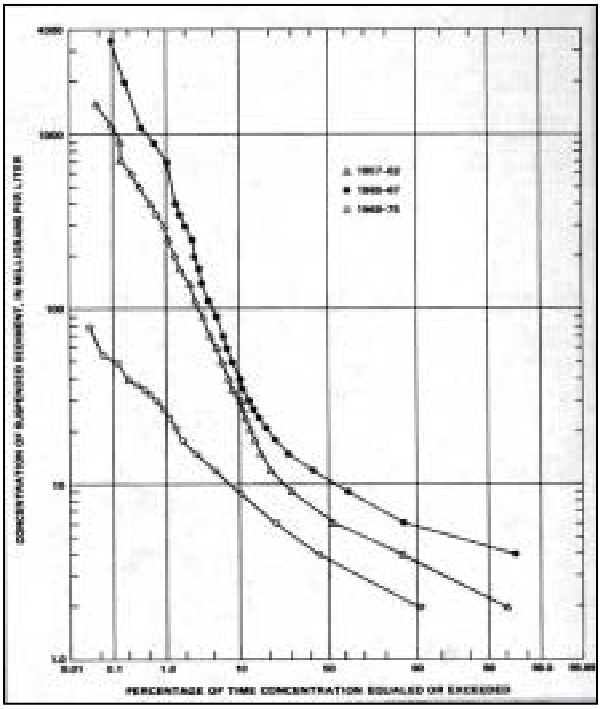

Figure 5.1-3. Cumulative Suspended Sediment Concentration-Frequency Curves for the Feather River at Oroville (USGS 1978)

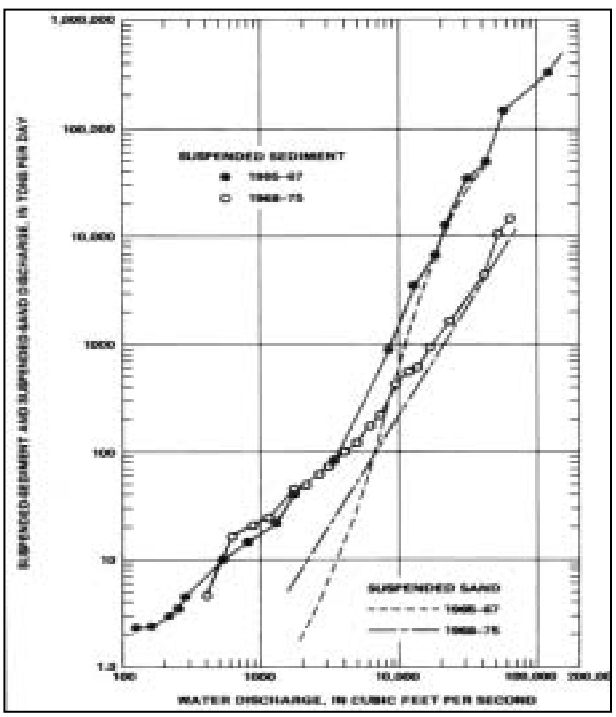

Figure 5.1-4. Relation between Streamflow and Suspended Sediment, Feather River near Gridley (USGS 1978)

pre-dam (1965-67) mean streamflow to be 5,970 cfs and the mean daily suspended sediment discharge to be 3,355 tons per day. Post dam streamflow was 5,521 cfs and the suspended sediment yield (1968-75) was 280 tons per day. Since there are no significant tributary inflows in the Oroville to Gridley reach of the river, the difference between the Oroville and Gridley gages of about 238 tons per day may result from channel bed and bank erosion, or inaccuracies in the data. Note also that the limited period of record occurs immediately after dam closure, and a significant amount of sediment may still have been in transit during this time period.

Figure 5.1-4 shows two years of pre-dam and seven years of post dam suspended sediment data. These graphs show a dramatic reduction in suspended sediment concentration from the pre- to post dam periods. The reduction is mostly for flows over 10,000 cfs. At higher flows of about 80,000 cfs, this is equivalent to an order of magnitude change in the amount of suspended sediment. With time, the amount of sediment in transport will decrease further as sediment in storage is moved out of the study reach.

Figure 5.1-5 shows the pre- and post dam cumulative suspended sediment concentration frequency curve. More recent sediment data have not been found.

The USGS (1978) computed the total sediment discharge suspended sediment and bedload) for this station, but only for the 1965 water year. The December 1964 flood occurred during the sampling period.

Total sediment discharge measurements

include determination of water discharge, mean velocity, width and depth of the stream, water temperature, concentration of suspended sediment, and of bed material. The total sediment discharge was then computed using the procedure outlined by Colby and Hembree (1955, in U.S. Geological Survey 1978). A summary of the data and computations are given by the U.S. Geological Survey (1978).

Total sediment was only calculated for the 1965 water year. The total suspended sediment load was 2.998 million tons. The calculated bedload, or unsampled load, load was 0.683 million tons, and the total was 3.68 million tons. Of this total, 74% moved in just ten days during the December 1964 flood.

5.1.3 Feather River at Yuba City Sediment Transport

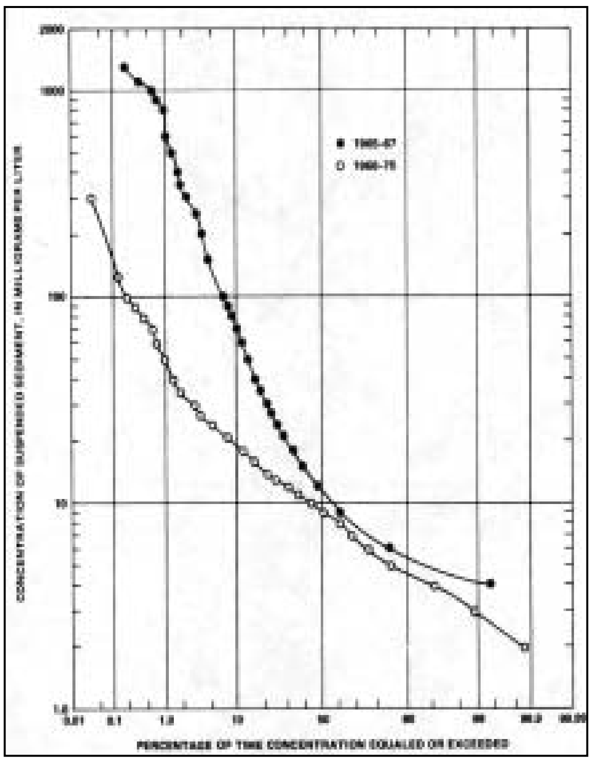

Figure 5.1-5. Cumulative Suspended Sediment Concentration-Frequency Curves for the Feather River near Gridley (USGS 1978).

This gage includes sediment inflow from the 77.7 square mile Honcut Creek drainage area. The pre-dam (1965-67) daily mean streamflow at the Yuba City gage was 6,325 cfs and the suspended sediment discharge was 3,806 tons per day. The post dam streamflow was measured as 5,889 cfs and sediment (1968-75) was estimated at 1,815 tons per day by the USGS. The yield is a combination of suspended sediment from Honcut Creek, pre-dam suspended sediment still moving out of the system, and river bank/bed erosion.

Figure 5.1-6 shows the suspended sediment and suspended sand concentration curves for the Yuba City gage. The pre- and post dam graphs do not show the large changes as was evident in the upstream gages. There are two reasons for this. The first is that the lower river has less hydraulic alteration. The second reason is the length of time needed for the fine sediment to move out of the system had not been reached.

The short time involved in the post dam analysis was not enough to move the sediment out of the system. The present yield is probably significantly less now than the 1967-75 study period.

The post dam drop in sediment yield is less noticeable at Yuba City than the upstream

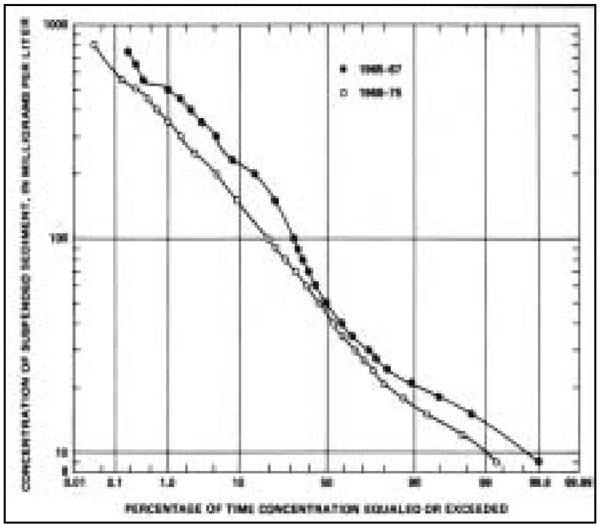

Figure 5.1-6. Cumulative Suspended Sediment Concentration-Frequency Curves, Feather River at Yuba City (USGS 1978).

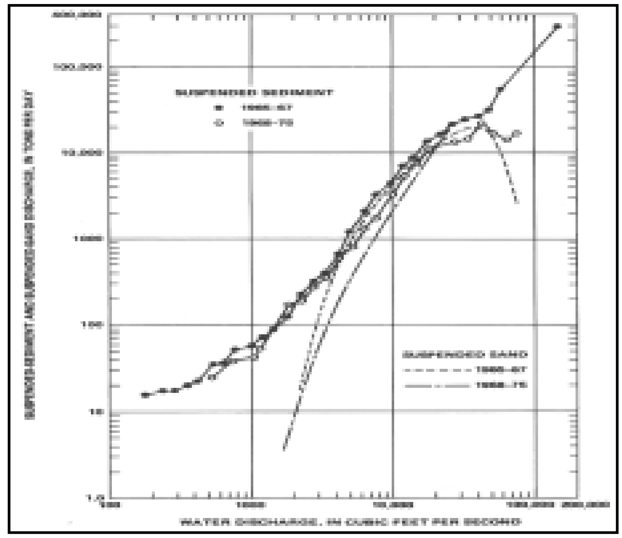

Figure 5.1-7. Relation between Streamflow and Suspended Sediment Discharge, Feather River at Yuba City (USGS 1978).

gages. However, as the accumulated deposits of fine sediment are moved out of the river system, we expect the sediment yield to drop. In addition, the river is still downcutting into hydraulic mining “slickens”, and this process is providing some suspended sediment to the river. Both pre- and post dam curves are presented. More recent sediment data have not been found, but it is suspected that this relation has significantly changed. Figure 5.1-7 shows the relationship between flow and suspended sediment for the Yuba City gage.

5.2 DEVELOPMENT OF A SEDIMENT MODEL

Alluvial rivers are self-regulating in that they adjust their characteristics in response to any change in the environment. These environmental changes may occur naturally, as in the case of climatic variation or changes in vegetative cover, or may be a result of such human activities as damming, river training, diversion, sand and gravel mining, channelization, bank protection, and bridge and highway construction. Such changes distort the natural quasi-equilibrium of a river; in the process of restoring the equilibrium, the river will adjust to the new conditions by changing its slope, roughness, bed-material size, cross-sectional shape, or meandering pattern. Within the existing constraints, any one or a combination of these characteristics may adjust as the river seeks to maintain the balance between its ability to transport sediment and the sediment load provided.

Modeling is particularly useful for understanding changes to the river’s natural state and predicting responses to human activities. Models can be used to determine the following:

- Predict future changes based on past changes,
- Determine the geomorphic effects of new structures such as bank protection, dams, bridges, etc prior to installation,
- Determine sediment transport, and sediment transport changes caused by dams and other structures.

5.2.1 Model Selection

Numerous sediment models are available. Four models were selected for further evaluation based on literature and peer review. These are: SAM (Sediment Analysis Model), Hydrologic Engineering Center's HEC-6, GSTARS 2.1, and FLUVIAL-12. These four models are the most commonly used for evaluating sediment transport and geomorphic changes.

SAM is primarily a sediment routing model that is not capable of modeling changes in channel cross-section, scour and fill, or bank erosion. It is useful for doing sediment analysis at specific points along the river, such as at gaging stations or bridges. It is not capable of doing movable boundary (bed erosion and deposition) or erodible boundary (bed and bank erosion and deposition) modeling.

HEC-6 is a one-dimensional movable boundary river model designed to simulate and predict changes in river profiles resulting from scour and deposition. Model inputs include HEC-2 compatible river cross-sections, river flow data (normally mean daily flow, but flood hydrographs may also be input), bulk sample channel bed sediment analyses, slope, roughness, and others. Outputs include sediment transport, cross-section changes, scour and deposition, changes in bed composition, armoring effects, changes in river profile, and others. HEC-6 is useful where river width or channel changes are not extensive. HEC-6 does not model bank erosion.

GSTARS is a new program that was developed by Molinas and Yang with assistance from the U.S. Bureau of Reclamation. It is free and is available on the internet. It has similarities to HEC-6 but has a graphical user interface for easier data entry. It has 14 different sediment transport equations to choose from. It does not model bank erosion.

FLUVIAL-12 was selected for this project. It is similar to HEC-6 in both input and output data. Both use HEC-2 hydraulic and cross-section data. FLUVIAL-12, however, has the additional benefit of being an erodible boundary model that can not only model changes in bed elevation but also channel width and bed topography induced by the channel curvature. In this way, bank erosion, changes in channel curvature, and river meandering can also be modeled. Both channel changes and bank erosion occur in the Feather River study reach. Results of the FLUVIAL-12 modeling are in Appendix A.

FLUVIAL-12 has been used by the DWR on another project and we have worked with Dr. Howard Chang, the model developer, on several related projects. Data inputs to the model are compatible with previous studies and available hydrologic data.

One additional benefit of this model is the ability to select sediment transport equations that best match river conditions. DWR studies on the South Fork Trinity and on Cottonwood Creek used the Parker equation as the most appropriate. Dr. Chang's preliminary analysis of the Feather indicates that the Parker equation under-estimates sediment yield. The Engelund-Hansen bedload transport equation appears to be the most appropriate available equation for the Feather River. This was determined by comparing the sediment rating curve prepared by the USGS (1978) with sediment output from the model at a variety of flows.

5.3 FLUVIAL-12 MODEL

The computer program FLUVIAL-12 is an erodible-boundary mathematical model that is formulated and developed for water and sediment routing in natural and man-made channels. The combined effects of flow hydraulics, sediment transport, and river channel changes are simulated for a given flow period. FLUVIAL-12 is capable of modeling changes over time in the following physical parameters:

- Channel scour and fill, aggradation and degradation.
- Changes in channel cross-section, including depth and width.
- Changes in bed material composition, including coarsening or fining. Armoring, the condition where the surface layer becomes coarser than the underlying bed material, is also predicted and modeled.
- Changes in cross-sections caused by bank erosion, sediment deposition, and meandering.
- Changes in water surface and bed elevation profiles.
- Changes in Manning's n, or the roughness of the channel.
- Changes in sediment transport.
- Changes in river curvature.

These inter-related changes are coupled in the model for each time step. While this model is for erodible channels, physical constraints, such as bank protection, grade-control structures and bedrock outcroppings, may also be specified. Applications of this model include evaluations of general scour at bridge crossings, sediment delivery, channel responses to sand and gravel mining, channelization, and dams. It has been applied to many designs for bank protection and grade-control structures which must extended below the potential channel bed scour and withstand the design flood.

An *erodible-boundary model* (FLUVIAL 12) is different from an *erodible-bed model* (such as HEC-6) in the following ways:

- An erodible-bed model does not simulate changes in channel width. Since changes in channel-bed profile are closely related to changes in width, these changes may not be separated.
- The change in bed profile in an erodible-bed model is assumed to be uniform in the erodible zone. All points adjust up and down by an equal amount during aggradation and degradation. Actual bed changes are by no means uniform and therefore they may not be simulated by an erodible-bed model.
- An erodible-bed model does not consider the channel curvature. In reality, the bed topography is highly non-uniform in a curved channel, especially during a high flow.
- The erodible zone needs to be specified at all cross sections in an erodible-bed model. This means the model does not provide the extent of erosion in the channel, but the user has to inform the model about the erodible part of the channel bed. The boundary of erosion is computed and provided by the FLUVIAL-12 model, this boundary changes with the discharge and time.
- Sediment flowing into the channel reach needs to be specified for many other models. This requires the sediment rating curve which is usually not available for stream channels. In the FLUVIAL-12 model, the sediment inflow may be specified and it may also be computed based on the hydraulics of flow at the upstream section at every time step.

The model has been developed for water and sediment routing in rivers while simulating river channel changes. River channel changes simulated by the model include channel-bed scour and fill (or aggradation and degradation), width variation, and changes caused by curvature effects. Because changes in channel width and channel-bed profile are closely inter-related, modeling of erodible channels must include both changes. In fact, width changes are usually greater than the concomitant scour and fill in the bed, particularly in ephemeral streams.

5.3.1 Model Assumptions and Inputs

Models are limited by the quality and quantity of the input data. Cross-section spacing, bed sampling intervals, availability of detailed hydrologic data, and others will affect the quality of the output data. Proper model calibration is essential, but this is dependent on the measured accuracy of cross-sectional changes. Selection of the proper and applicable sediment transport equation is also essential. The assumptions and inputs to the model are described in detail in Appendix A.

Some of the assumptions used in the FLUVIAL-12 model are the following:

- Cross-sections used in the analyses are adequate representations of the stream channel at all flows.
- The roughness coefficient remains static at all levels of flow.

- The geometric mean of the bed material size fractions adequately describes the sediment size distribution.
- The selected sediment transport equation properly represents sediment movement at all discharges.
- The river channel is in dynamic equilibrium at all discharges.
- There is uniformity in sediment discharge, power expenditure, energy gradient, water surface slope, and other elements in the short reaches between cross-sections.
- That the spatial and temporal variations in flow, sediment transport, and channel geometry, are adequately modeled with iterative time, cross-section, and flow data.

The model has the following five major components: (1) water routing, (2) sediment routing, (3) changes in channel width, (4) changes in channel-bed profile, and (5) changes in geometry due to curvature effect. These inter-related components are described in the following sections.

Water routing is the most significant component. Water routing is an input value that provides temporal and spatial variations of the stage, discharge, energy gradient and other hydraulic parameters in the channel. It has the following three major features: (1) Numerical solution of the continuity and momentum equations for longitudinal flow, (2) evaluation of flow resistance, and (3) upstream and downstream boundary conditions. Input values of hourly and daily flow data are readily available from CDEC and the USGS.

The magnitude, timing, duration, rate of change and frequency of flows are inputs to the model. The time-scales are those allowed by the existing data, mostly daily, but also monthly, hourly, or in 15-minute increments. A series of tables, charts, and graphs are generated from the streamflow gaging data including: monthly flow statistics tables summarizing mean monthly flow and monthly exceedance flows; tables summarizing average monthly flow; tables summarizing mean daily flow for each year of the period of record; duration curves depicting the median flow for each station. These are presented in the Task 1.2 report.

The second major component of the model is sediment routing. It has the following major features: (1) Computation of sediment transport capacity using a suitable formula for the physical conditions, (2) determination of actual sediment discharge by making corrections for sorting and diffusion, (3) upstream conditions for sediment inflow, and (4) numerical solution of the continuity equation for sediment. These features are evaluated at each time step, and the results are used in determining changes in channel configuration.

Change in the channel width is the next component. An increase in width at a channel section depends on sediment removal along the banks. The maximum rate of widening occurs when sediment inflow from the upstream section does not reach the banks of this section while bank material at this section is being removed. River banks have different degrees of resistance to erosion, resulting in different rates of sediment removal. The model uses a bank erodibility factor ranging in value from 0 (non-erodible banks) to 1 (easily erodible banks).

A decrease in channel width is accomplished by sediment deposition along the banks or by a decrease in stage, or both. For practical reasons, deposition does not exceed the stage in the model. The maximum amount of width reduction at a section occurs when sediment inflow from the upstream section is spread out at this section and the sediment removal from the bank areas at this section is zero. Within the limit of width adjustment, changes in width are made at all cross sections in the study reach toward establishing uniformity in power expenditure.

The fourth component in the model is change in channel bed profile. Distribution of erosion and deposition, or scour and fill, at a cross section is usually not uniform. Generally speaking, deposition tends to start from the low point and is more uniformly distributed because it tends to build up the channel bed in nearly horizontal layers. This process of deposition is often accompanied by channel widening. On the other hand, channel-bed erosion tends to be more confined with greater erosion in the thalweg. This process is usually associated with a reduction in width as the banks slip back into the channel. Such characteristic channel adjustments are effective in reducing the variation in stream power as the river seeks to establish a new equilibrium.

The fifth component is change in geometry due to curvature effects. Typically, scour-related effects occur on the outside of a bend where velocities are the highest. Deposition, in contrast, generally occurs on the inside of the bend. Simulation of curvature-induced scour and deposition in the model is based on the flow curvature which varies across the channel.

Data requirements for the model are as follows:

- Topographic maps of the Feather River. These maps should show locations of cross sections used for the HEC-2 study, if any.
- Available digitized cross-sectional data used for HEC-2 studies for the stream reach from the downstream end to the upstream end of study.
- Mean daily river flow data for the period of record. Peak discharges and flood hydrographs of 10-, 50- and 100-yr floods and their variations along the study stream reach.
- Existing mining sites and proposed mining plans, if any.
- As-builts and locations of existing bridges, drop structures, bank protection, levees, etc.
- Sediment samples along the study reach and each tributary stream. Size distributions of such samples are normally determined based on the sieve analysis.

The HEC-2 format for input data is used in all versions of the FLUVIAL-12 model. Data records for HEC-2 pertaining to cross-sectional geometry (X1 and GR), job title (T1, T2, and T3), and end of job (EJ), are used in the FLUVIAL-12 model. If a HEC-2 data file is available, it is not necessary to delete the unused records except that the information they contain are not used in the computation.

5.3.2 Calibration

The accuracy of a mathematical model depends on the physical foundation, numerical techniques, and physical relations for momentum, flow resistance and sediment transport. Test and calibration are important steps to be taken for more effective use of a model. Because of the difference in sensitivity of simulated results to each relation or empirical coefficient, more attention needs to be paid to those that generate sensitive results. Major items that require calibration include the roughness coefficient, sediment transport equation, bank erodibility factor, bed erodibility factor, and so on. Calibration of the model is described in detail in Appendix A.

To determine the sensitivity of flow, the sediment transport, and the channel changes caused by the variation of each variable, different values of the variable need to be used in simulation runs and the results so obtained are compared. Generally speaking, the rate of channel changes is more sensitive to the sediment rate computed from a sediment equation but the equilibrium channel configuration is less sensitive. It may also be stated that the rate of widening is sensitive to the bank erodibility factor but that the equilibrium width is not nearly as sensitive.

Field data are generally used for test and calibration of a model. The required information includes channel configuration before and after the changes, a flow record, and sediment characteristics. Data sets with more complete information are also more useful. The FLUVIAL-12 has undergone test and calibration using many data sets. In Northern California, these include the San Lorenzo Creek, Stony Creek, and the Upper Feather River (Appendix A).

The ideal method of calibration, referred to as Type1 consists of running the model between two known end conditions. This requires detailed knowledge of channel conditions (cross-sections, bed material, roughness, and etc.) at the beginning of the calibration run, and at the end. The model is run using the initial conditions and adjusted until the model produces the final condition.

Type1 calibration is generally not possible because the initial data are generally not available. This is the case for most fluvial modeling projects and also the Feather River. There is a lack of detailed cross-section, bed material, roughness, surface water profiles, and other data for the initial conditions.

Type 2 calibration was done for this project. This type of calibration consists of using available data sets and estimating the unknown values. The unknown values are adjusted until the known initial and final conditions match.

Model outputs can also be calibrated with data from Task 4 and with painted and radio-tagged rocks. These rocks have been placed in the river in a number of selected places, and are being monitored through the winter season to determine at what flows the rocks begin to move. Rocks were color-coded according to location. Radio-tagged rocks are first drilled using a rock bit then a small radio transmitter or transponder is inserted, and sealed using epoxy. A radio receiver or oscilloscope is being used periodically to monitor movement after significant flow events have occurred.

Channel roughness coefficients were selected using a USACE's (1997) HEC-2 hydraulic model for the Feather River and modifying the values as needed based on field inspection and calibration procedures. Calibration was also done using observed water surface elevations and profiles and comparing with those calculated in the model.

Channel bed profiles and cross-sections from the USGS (1972) were compared to the USACE's (1997) HEC-2 profiles and cross-sections. The data shows that there has been a general degradation trend, which was incorporated into the model. Initial channel bed material size classification was estimated based on sediment samples collected in 1979 and 1980.

There are a number of overflow weirs into the OWA. These begin to spill when the discharge exceeds about 50,000 cfs. Engineering analyses and comparison of flood hydrographs indicate that the weirs have minor effects on Feather River streamflow and can be ignored in the calibration and the modeling.

Probably the most important calibration procedure is the selection of the appropriate sediment transport formula. Three formulas were used to compute average sediment discharge for the Low Flow Reach. These were the Parker, Ackers-White, and Engelund-Hansen.

The bedload computed using the Parker formula showed a value of zero, even for major storm events. The other two formulas showed movement, but the Engelund-Hansen equation results are more similar to the measurements made by the USGS (1978), and therefore was the equation selected.

However, the USGS measurements were made between 1968 and 1975, and the model calculations used current bed material compositions. The USGS measurements were also done directly after dam closure, and before the sediment had a chance to flush from the Feather River.

Bank erodibility was calibrated using bank composition and historic meander data from aerial photographs. Each geologic unit was assigned a bank erodibility factor based on the natural erosion resistance. The factor (shown in Appendix A) was adjusted based on erosion measurements from ortho-rectified aerial photos and survey maps. The flood series from 1972 to 1997 was used to simulate channel changes and bank erosion.

5.3.3 Model Outputs

Model outputs include changes in channel scour and fill, bed material load, sediment delivery, bed material, roughness, bank erosion, cross-section changes, gradient, and sediment transport. Hydraulic conditions such as bottom shear stress, velocity, and wetted hydraulic radius are also model outputs as needed.

A bedload transport curve showing the relation between water and sediment discharge is also an output. A detailed description of model outputs is in Appendix A.

The main purpose of the model was to run a simulation for 50 years to determine ongoing and future changes resulting from project operations. Hydraulic simulations to determine initial gravel bed motion, sediment transport rates, channel changes (aggradation or degradation), slope change, bed armoring have also been done.

One of the primary uses of the model is to evaluate Resource Actions. Resource Actions are protection, mitigation, and enhancement measures to be agreed upon during the Settlement Negotiations. One such Resource Action is in-channel spawning gravel placement. For example, the model can be used to determine at which flows the gravel bed begins to mobilize. This is critical in determining flow conditions that degrade spawning riffles. It is also important in designing spawning gravel rehabilitation measures. The model is a useful tool for predicting future changes caused by various hydraulic scenarios.

5.4 FLUVIAL-12 MODELING RESULTS

Dr. Howard Chang, fluvial engineer conducted the modeling activities. The results of the modeling are presented in Appendix A and are summarized in this report.

5.4.1 Sediment Model Outputs

The model study identifies the hydraulic, geomorphic, and sediment transport changes that have occurred from 1967 to the present, and predicts changes that will occur in 50 years. The following is a list of model outputs:

1. Changes over time in channel depth, width, and cross-sectional area.
2. Changes over time in water surface profiles.

3. Changes in roughness coefficient and bed material size fractions.
4. Locations of channel scour and fill.
5. Changes in Thalweg profile
6. Velocity and flow required to mobilize the bed sediment sizes at each cross-section.
7. Bed material load moving past each cross-section during the study period.
8. Sediment delivery, or the total bed material yield during the study period.
9. Bed material armoring.
10. Bank erosion and channel movement.

Model outputs can be specified at any time during the model run and at any cross-section. For this study, the model was calibrated over a 25- year time period, then run with an output at 50 years.

5.4.2 25 Year Model Calibration Results

As part of the calibration procedure, the model was run for the 25 year period between 1972 and 1997. This time period captures the 1976-77 drought, the February 1983 and March 1986 floods, the 1986-93 drought, and the 1997 flood. The results include variation in sediment delivery, channel geometry, and sediment size.

5.4.2.1 Variation in Sediment Delivery

Sediment delivery is the cumulative amount of sediment that has passed a certain point for a specified amount of time. The spatial variation in sediment delivery along a channel reach is caused by sediment deposition and erosion. Deposition signifies that sediment is stored in the channel, resulting in aggradation at the cross-section and a reduced sediment delivery downstream. Erosion results in channel degradation and increased sediment delivery. A uniform sediment delivery indicates a balance with neither erosion nor deposition.

The 25 year sediment delivery is shown in Figure 5.4-1. The figure shows the amount of sediment moving past each river mile during the calibration period. The figure shows that the Feather River between the Fish Diversion Dam and Honcut Creek is not uniformly eroding, but also has areas where deposition is occurring.

Sediment delivery is the cumulative amount of sediment that has passed a certain point for a specified amount of time. The spatial variation in sediment delivery along a channel reach is caused by sediment deposition and erosion. Deposition signifies that sediment is stored in the channel, resulting in aggradation at the cross-section and a reduced sediment delivery downstream. Erosion results in channel degradation and increased sediment delivery. A uniform sediment delivery indicates a balance with neither erosion nor deposition.

The upper part of the low flow reach above RM 66 is an armored cobble bed set in bedrock. Only a minimal amount of sediment from bank erosion is introduced to the river, as shown in the figure. Sediment delivery then increases downstream and peaks at RM 62, mainly because of bank erosion. Sediment delivery drops to nearly zero at RM 61. This is caused by sediment depositing in a large gravel pit. At higher flows, most of the bedload would enter the pit. This has management implications in that any gravel augmentation to the river introduced above the pit would eventually deposit in the pit.

The sediment inflow into the study reach is cut off by Oroville Dam. About 3,000 cubic yards of spawning gravel was introduced into the river channel in 1982 as part of a mitigation project. The amount of delivery in the Feather River passing the Thermalito Outfall to the Feather River (Low Flow Reach) is modeled at 200,000 tons in the 25 years, or 8,000 tons per year. Because Oroville Dam has cut off the sediment supply, the yield is a result of bank and channel erosion. Finer sediments are more easily removed from the channel boundary, leaving the coarser sediment behind. The selective sediment transport has resulted in the gradual coarsening of the bed material. The amount of gravel moving out of the Low Flow Reach would be greater if sediment was not being trapped in the gravel pit at RM 61.

Input to the High Flow Reach during the 25 year calibration period was about 200,000 tons. The output from the HFR is about 1.5 million tons, indicating that bank and bed erosion is occurring. The process is not uniform. Deposition is significant at RM 54, 52 and 47, and erosion occurs in between, but predominately between RM 59-56, 52-48, and 47-44. Sediment output from the High Flow Reach is 1.4 million tons, of which 1.2 million tons are derived from bed and bank erosion, and 200,000 tons from the low flow reach.

The figure shows that the post Oroville channel is not in equilibrium. Deposition and erosion will continue well past the 25 year mark although the rate of change will drop with time.

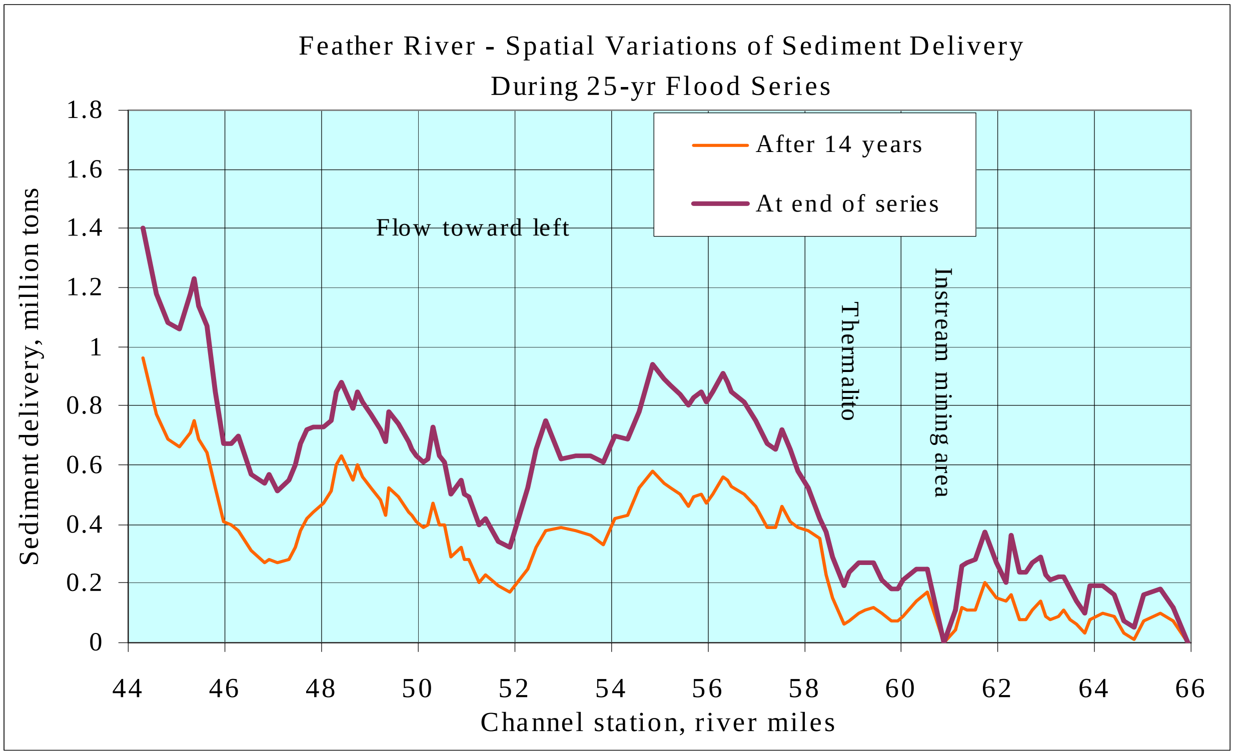

Figure 5.4-1. Spatial Variation of Sediment Delivery during the 1972-97 Flood Series (Chang 2003)

5.4.2.2 Variation in Channel Geometry

The changes in channel cross-sectional area and geometry at the end of the 25 year calibration period are best shown with cross-sections. Appendix A shows the changes in cross-section. In general, some cross-sections show degradation and others aggradation. There was an overall lowering in channel bed profile during the study period, caused by the removal of sediment from the bed.

Only a few of the cross-sections show significant bank erosion in the Low Flow Reach. These occur at about RM 61.5 to 62. The maximum erosion shown on these cross-sections is about 100 feet.

Lateral migration of channel bends are also predicted by the model. Bank erosion changes the channel curvature and the movement of sediment through a bend. This results in a change in location of the channel thalweg to the outside of the bend. In the High Flow Reach, bank erosion is minimal, except for the reach between RM 46.5 and 45.5 where up to 700 feet of bank erosion occurred in one area. Erosion also occurs downstream, but the model did not extend to this area. Figure 5.4-2 shows an example of a cross-section in the Low Flow Reach where this type of movement has occurred. All the FLUVIAL-12 modeled cross-sections are shown in Appendix A.

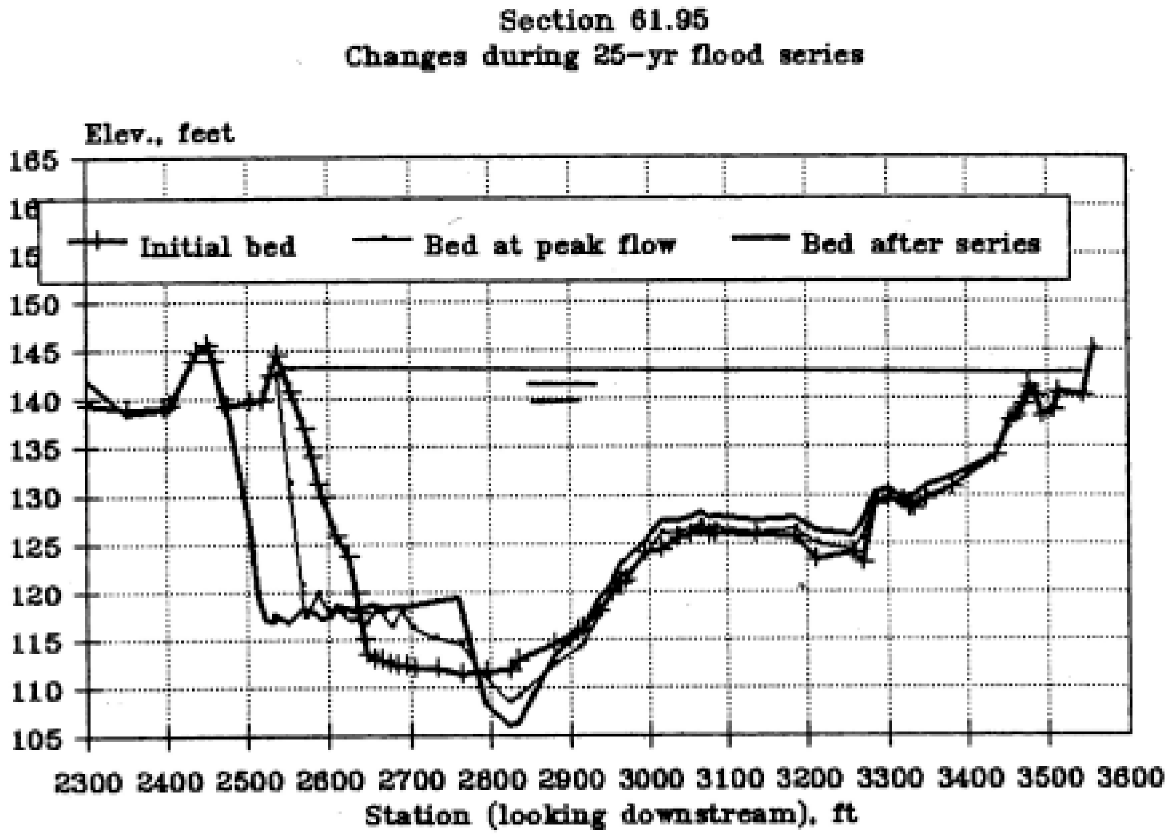

Figure 5.4-2. FLUVIAL-12 Cross-Section at RM 61.95, Showing Bank Erosion and Lateral Migration

5.4.2.3 Variation in Bed Material Diameter

Figure 5.4-3 shows the initial and final mean bed material diameter after the introduction of 3,000 cubic yards of spawning gravel. For the initial condition, there is a general and natural decrease in sediment size in the downstream direction, caused by a decrease in gradient and stream power. This is reflected in both the initial and final conditions.

The introduction of small amounts of spawning gravel has limited effects on bed material composition. The movement of the gravel is highly dependent on flow. The gravel may stay in one place for years if high flows do not occur. However, a single flood event will distribute the gravel over much of the study reach. Gravel moving as bedload may also be trapped in the gravel mining pits between RM 61 and 62.

After one year of higher flows, the bed material was almost as coarse as initial conditions. Coarsening is related to sediment sorting during the erosion process and finer sediment movement out of the study reach. This suggests that managing spawning gravel will require ongoing gravel injections. Another management implication is that the coarser the sediment injected into the river, the longer it will remain in the system.

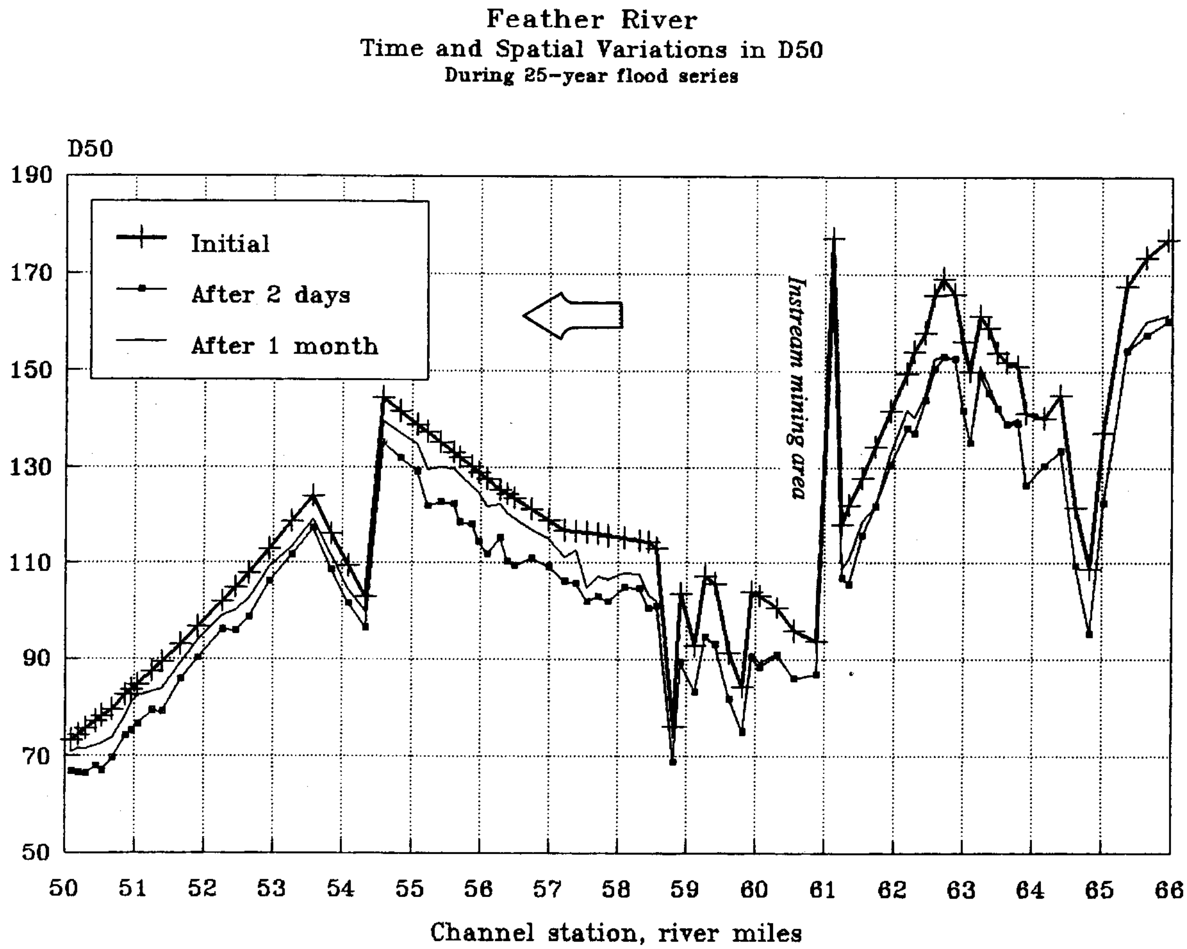

Figure 5.4-3. Spatial and Time Variations in Sediment Size due to Sediment Introduction.

Figure 5.4-4 shows the initial and final mean (D50) bed material diameter after a 25-year calibration run. First, there is a natural decrease in sediment size in the downstream direction, caused by a decrease in gradient and stream power. This is reflected in both the initial and final conditions. The model run shows a dramatic increase in the sediment size after 35 years. The largest increase was directly below the Fish Barrier Dam, with a D50 increase from 90 mm to 185 mm. At Rm 62, an instream mining area, the coarsening is from 55 mm to 120 mm. Sediment deposition in the mining area, and bed erosion directly below (at RM 61), results in a sharp increase in bed material size from 130 to 190 mm. At RM 44, the size increased from a D50 of 30mm to 55 mm.

The bed material size increase is similar to actual sampling conducted by DWR between 1980 and 2003, reported in the Task 2 report. There is limited information as to the coarsening of bed material in riffles and the consequent effects on salmon spawning. The coarsening affects the ability of the salmon to excavate the bed during redd construction. Armoring by cobbles too large for the salmon to move may limit the area in a riffle available for spawning. The eggs may also wash out of the gravel if the intragravel interstices are too large.

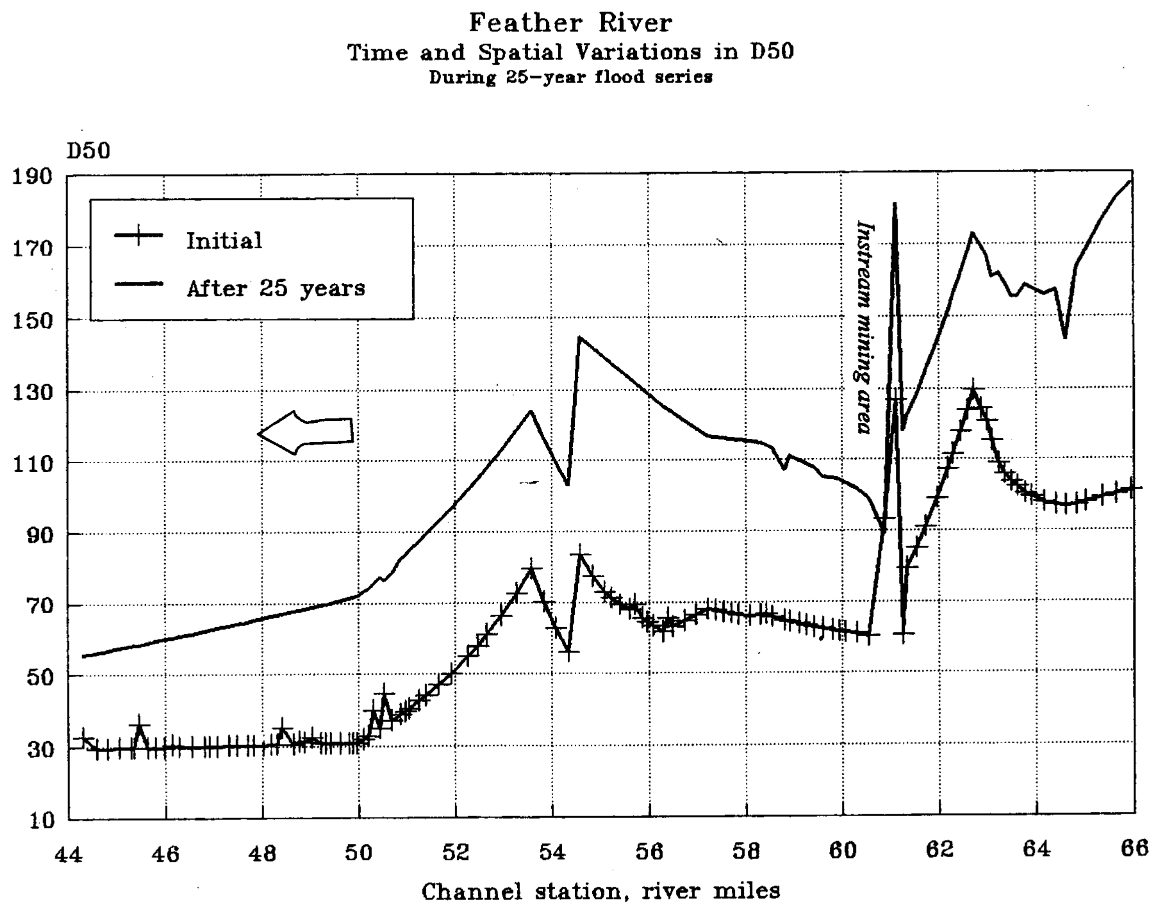

Figure 5.4-4. Spatial and Time Variations of Sediment Size during the 25-year Flood Series.

5.4.2.4 Variation in Thalweg Profile

Changes in channel geometry occur as sediment is washed out the system. These changes are important to the biological function of the stream system. Changes in depth, width, gradient, location of the thalweg, and other geomorphic factors affect the mesohabitat. These changes, in turn, affect the amount of riffle, run, or pool habitat.

Figure 5.4-5 shows the modeled water surface and channel thalweg profiles. The 25 year modeling run shows that channel bed degradation is predicted at most cross-sections, and aggradation at some locations. The channel degradation is consistent with the continued erosion. Future changes will be limited by bed armoring, which in turn, will reduce bed erosion and sediment yield. Knowledge regarding stream sections undergoing degradation is important in designing gravel augmentation projects and locating rehabilitation sites.

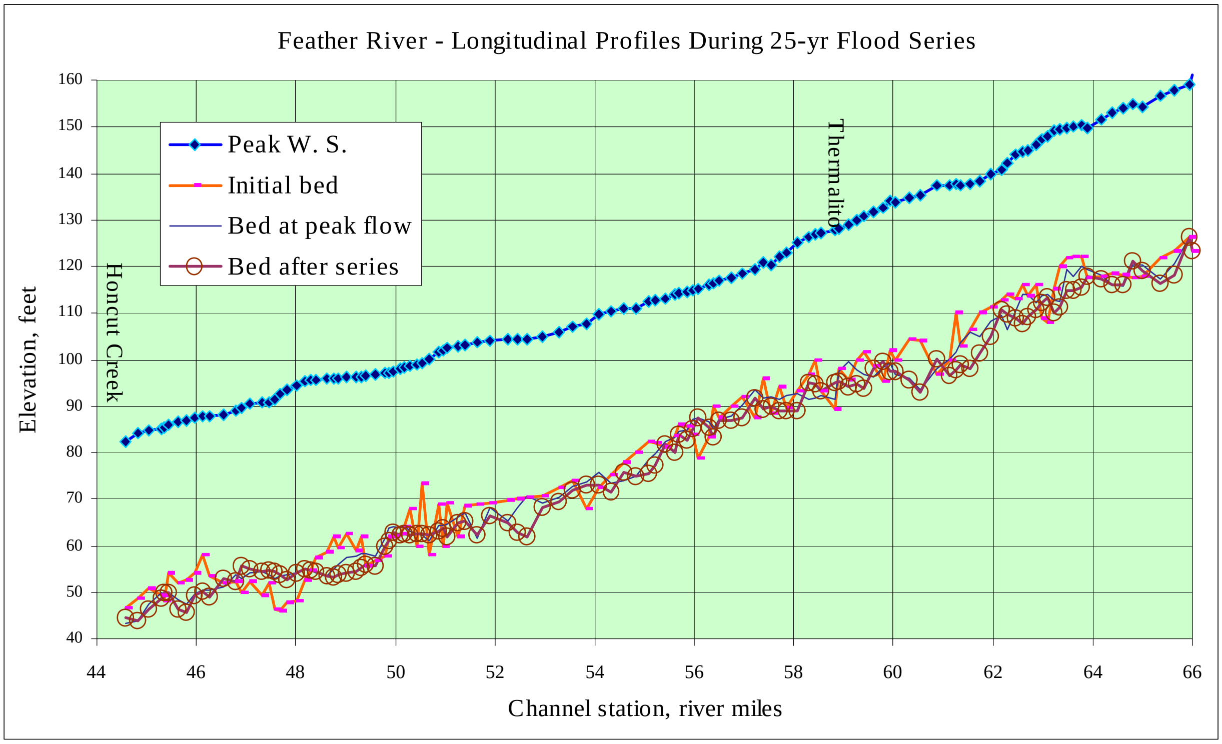

Figure 5.4-5. Water Surface and Channel Bed Profile Changes during Flood Series (Chang 2003).

5.4.3 50-Year Model Results

The main model purpose was to predict future ongoing changes for the next 50 years. This is the preferred relicensing time frame. Dr. Chang ran the 50-year model with two separate initial conditions (see Appendix A). One was for a natural non-armored bed, and the other was for an armored bed. Only the armored bed results will be discussed here since the initial armored condition models ongoing changes for the next 50 years.

5.4.3.1 Variation in Sediment Delivery

Sediment delivery predicted for the next 50 years is shown in Figure 5.4-6. The figure shows the amount of sediment moving past each river mile. The figure shows that the Feather River between the Fish Diversion Dam and Honcut Creek is not uniformly eroding, but also has areas where deposition is occurring. These areas have been tentatively identified as past gravel mining areas. The location of sediment traps is important in designing Resource Actions such as gravel augmentation projects. The net bed material yield from the Low Flow Reach are about 0.5 million tons in 50 years.

The pattern of sediment delivery shows a sharp rise in delivery in the Feather River just below the Thermalito Afterbay confluence. This is related to the increase in flow from Thermalito Afterbay and therefore an increase in erosion from the channel boundary.

The net bed material yield for the High Flow Reach to Honcut Creek is about 3.2 million tons after 50 years. Of this quantity, 2.7 million tons was eroded from the bed, and the remainder introduced as yield from the Low Flow Reach.

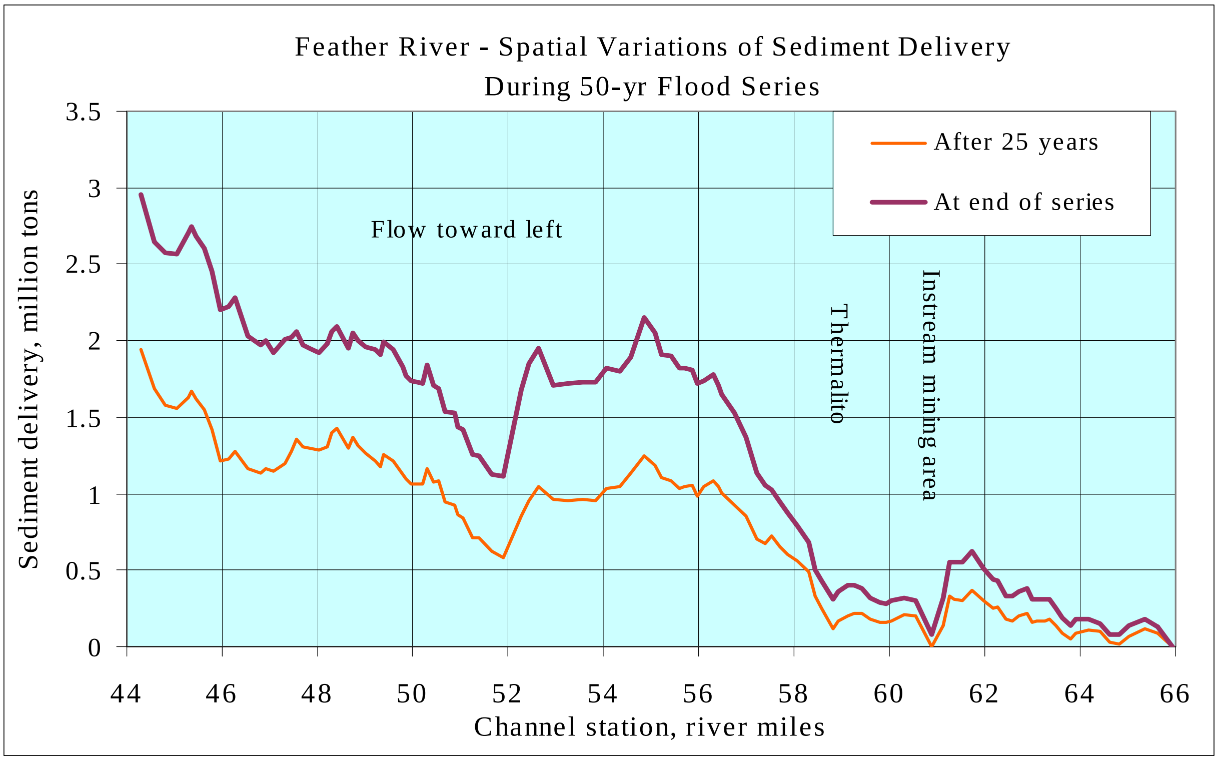

Figure 5.4-6. Time and Spatial Variation of Sediment Delivery during the 50 Year Flood Series for Armored Bed.

5.4.3.2 Variation in Bed Material Diameter

Finer sediments are more easily removed from the channel boundary, leaving the coarser sediment behind. The selective sediment transport has resulted in the gradual coarsening of the bed material.

Figure 5.4-7 shows the initial and final mean bed material diameter after a 50-year post dam model run. First, there is a natural decrease in sediment size in the downstream direction, caused by a decrease in gradient and stream power. This is reflected in both the initial and final conditions. The model run shows a dramatic increase in the sediment size after 50 years. The largest increase was directly below the Fish Barrier Dam, with a D50 increase from 120 mm to 190 mm. At RM 62, an instream mining area, the pit becomes finer from deposition, but the areas below becomes coarser, from 60 mm to 80 mm. At RM 44 near Honcut Creek, the size increased only slightly from a D50 of 30 mm to about 40 mm.

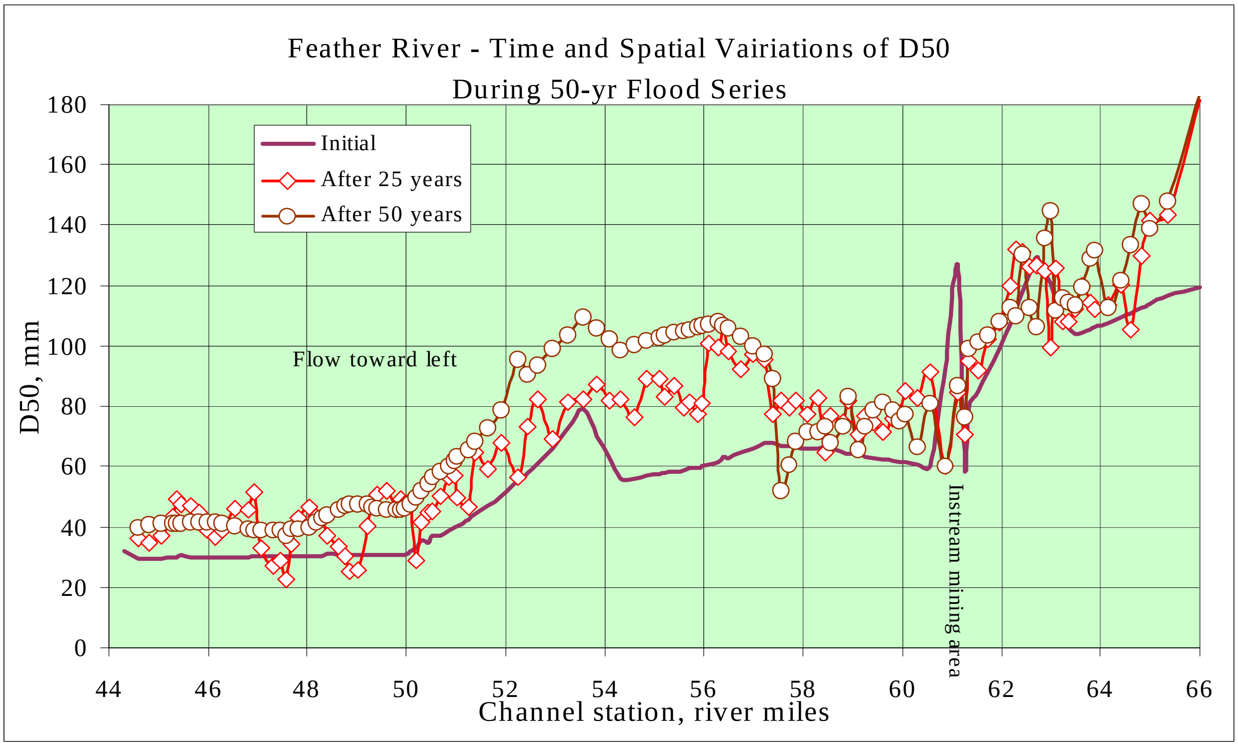

Figure 5.4-7. Time and Spatial Variations of Median Grain Size during the 50 Year Flood Series for Armored Bed.

5.4.3.3 Variation in Channel Geometry

Changes in channel geometry occur as sediment is washed out the system. These changes are important to the biological function of the stream system. Changes in depth, width, gradient, location of the thalweg, and other geomorphic factors affect the mesohabitat. These changes, in turn, affect the amount of riffle, run, or pool habitat.

Figure 5.4-8 shows the modeled water surface and channel thalweg profiles. The 50 year modeling run shows that channel bed degradation is predicted at most cross-sections, and aggradation at some locations. The channel degradation is consistent with the continued erosion. Future changes will be limited by bed armoring, which in turn, will reduce bed erosion and sediment yield.

The bed material size increase is similar to actual sampling conducted by DWR between 1980 and 2003, reported in the Task 2 report. There is limited information as to the coarsening of bed material in riffles and the effects on salmon spawning. The coarsening affects the ability of the salmon to excavate the bed during redd construction. The eggs may also wash out if the intragravel interstices are too large.

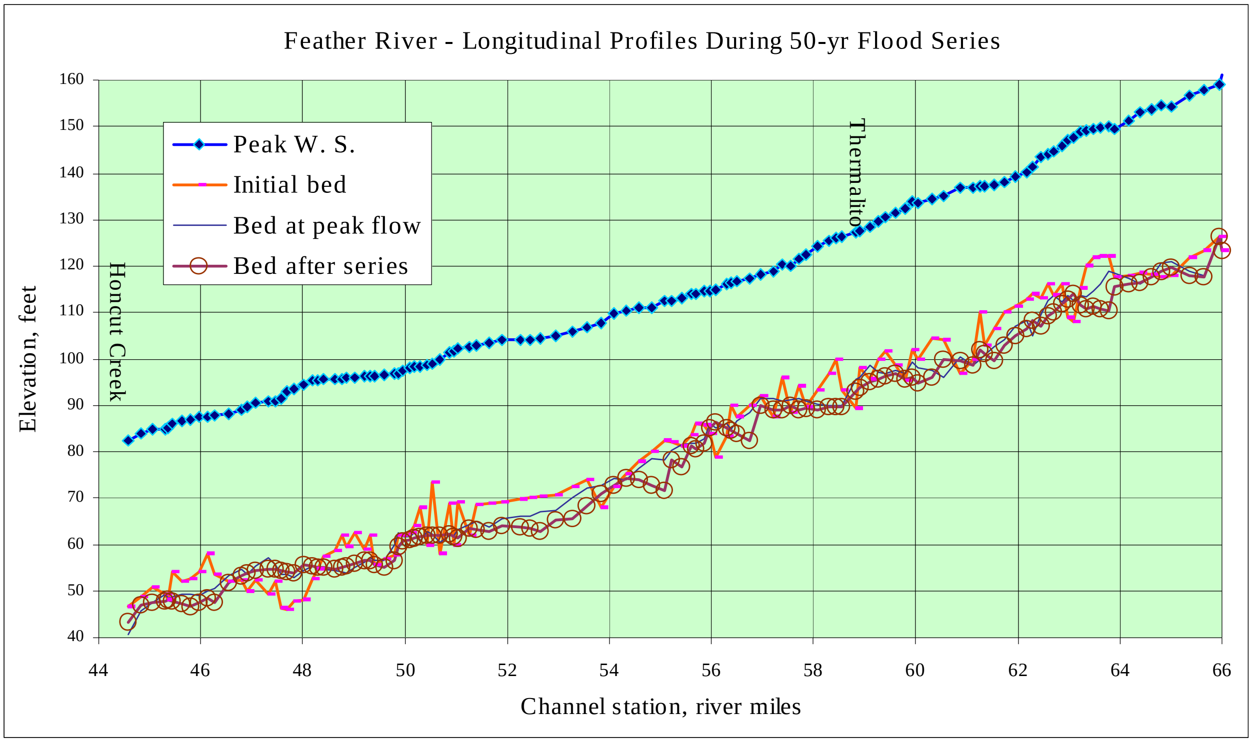

Figure 5.4-8. Water Surface and Channel Bed Profile Changes during the 50 Year Flood Series for Armored Bed.

Lateral migration of channel bends are also predicted by the model. Bank erosion changes the channel curvature and the movement of sediment through a bend. This results in a change in location of the channel thalweg to the outside of the bend. Figure 5.4-9 shows an example of a cross-section where this type of movement has occurred. All the FLUVIAL-12 modeled cross-sections are shown in Appendix A.

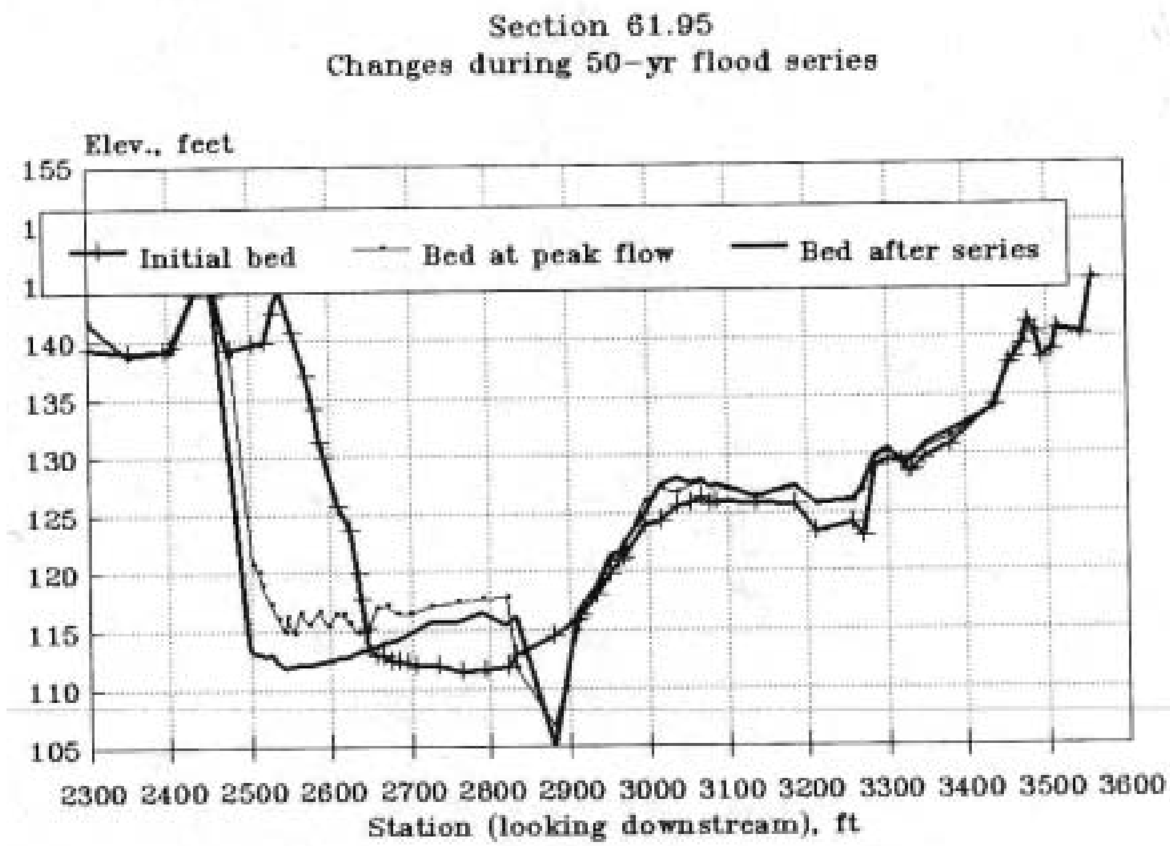

Figure 5.4-9. Cross-Section 61.05 Showing 50 Years of Lateral Erosion.

5.4.3.4 Initiation of Bed Movement

Figure 5.4-10 shows the flows for initiation of bed motion, or where particles of a certain geometric mean diameter will begin to move. The flow shown on the graph is the flow where about half of the cross-sections show movement in that size range. Both the Low Flow and the High Flow reaches are shown.

Flow velocities vary over riffles and pools. Consequently, the channel bed shear stress varies from location to location, both laterally and downstream. Shear stress also generally increases with increasing water discharge. Usually, the maximum shear stress and incipient bed material motion occurs at the thalweg.

The FLUVIAL-12 model was run to investigate initial bed motion. The average flow condition of a channel reach was used. Under this condition, about half of the cross-sections show little or no motion, but the other half show limited sediment motion. The figure shows that the Low Flow Reach can move larger diameter gravel than the High Flow Reach at the same discharge. For example, at 10,000 cubic feet per second, the low flow reach will begin to transport 1.25 inch gravel, and the High Flow Reach will transport 0.75 inch gravel.

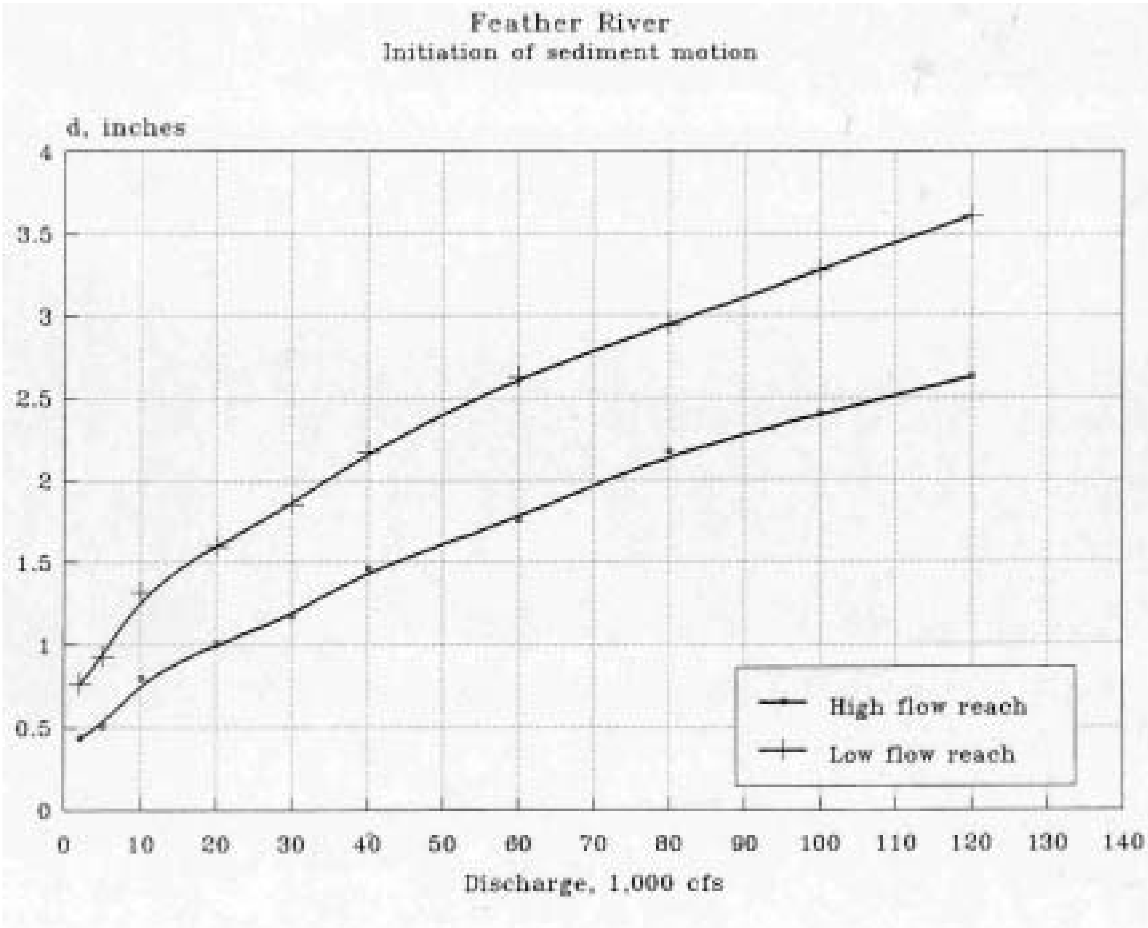

Figure 5.4-10. Sediment Grain Size in Relation to flow Discharge at Initiation of Motion.

6.0 CONCLUSIONS

We conclude the following about hydraulic and sediment transport modeling with FLUVIAL-12 in the Feather River below Oroville Dam:

- The amount of sediment transport is less than pre-Dam conditions. Sediment transport data were available from the U.S. Geological Survey (1978) for a short time period directly after the construction of project facilities. The average annual pre-dam sediment yield at the Feather River at Oroville gage was estimated to be 3,264 tons per day (1902-62). The post dam yield (1968-75) was estimated at 42.5 tons per day.
- The sediment inflow into the study reach is cut off by Oroville Dam. The amount of bed material load in the Feather River passing the Thermalito Outfall (Low Flow Reach) is modeled at 0.5 million tons, or about 10,000 tons per year, or 27 tons per day. This is about half of the yield calculated by the USGS between 1968 and 1975. The yield is primarily a result of channel erosion since bed material is trapped by Oroville Dam.
- The pattern of sediment delivery shows a sharp rise in delivery in the Feather River just below the Thermalito Afterbay confluence. This is related to the increase in flow from Thermalito Afterbay and therefore an increase in erosion from the channel boundary. The net bed material yield for the High Flow Reach to Honcut Creek is predicted to be about 3.2 million tons after 50 years, or about 175 tons per day. Of this quantity, 2.7 million tons is eroded from the bed, and the remainder introduced as yield from the Low Flow Reach.
- Lateral migration of channel bends are predicted by the model. The amount of bank erosion in the Low Flow Reach is small, a reflection of the stable banks consisting of erosion resistant bedrock, terrace deposits, and cobbly dredger tailings. The largest lateral bank movement occurs on the left bank directly above the Robinson gravel mining pit. Most of the bank erosion in the modeled reach occur in the High Flow Reach in three places within several miles above the Feather River's confluence with Honcut Creek. Cross-sections in this area show lateral migration. However, because of the placement of cross-sections, a better prediction of future lateral migration is based on aerial photography interpretation in the Task 5 Report.
- The Engelund-Hansen equation best emulates bed material movement in the study reach. The model was run using a number of different sediment transport equations. The Engelund-Hansen equation was selected because the results most closely resembled sediment transport data measured by the USGS (1978).
- The modeling shows that spawning size gravel are transported at moderate and high flows that occur a number of times each ten year period. One inch gravel begins to move at about 5,000 cfs in the Low Flow Reach, and 20,000 cfs in the High Flow Reach. Three inch gravel begins to move at 80,000 cfs in the Low Flow and over 130,000 cfs in the High Flow Reach.

- Resource Actions such as spawning gravel placement and side channel habitat development will have to be designed with gravel retention structures, or gravel will have to be replenished on a periodic basis. For example, the model would be used to determine at which flows the gravel bed begins to mobilize at riffle locations. Gravel injected near the top of the study reach is transported downstream during storm events, and lower the median grain size.
- The location of sediment traps is important in designing Resource Actions such as gravel augmentation projects. Abandoned instream gravel mining areas and pits will capture spawning gravel injected into the river above.
- The channel between the Fish Barrier Dam and Honcut Creek has become armored. Armored beds are a result of a loss of sediment supply and the removal of the finer bed material by high flows. Finer sediments are more easily removed from the channel boundary, leaving the coarser sediment behind. The selective sediment transport has resulted in the gradual coarsening and armoring of the bed material. In some places, the bed armoring may be too coarse for the salmon to build redds. The largest increase in size was directly below the Fish Barrier Dam, with a D50 increase from 120 mm to 180 mm and at River Mile 56, with an increase from 60mm to 110mm.
- The pattern of sediment delivery shows a sharp dip at the Robinson gravel mining pond near RM 61. The low levee separating the pond and the river has been breached, and most of the river flows into the pond. Most of the bed material load from above is deposited in the pit. Sediment starvation below the pit results in bed armoring and a dramatic increase in mean gravel size on Robinson Riffle compared to riffles above and below. Only a small part of the streamflow now flows across the Robinson Riffle area, further degrading the spawning habitat.
- Those reaches near mining areas are subject to greater changes in river planform, bank erosion, channel migration, and degradation than other areas. This is because of the disruption in channel profile and cross-section, resulting in sediment deposition within the mining areas and scour and degradation in the areas above and below.
- The pattern of sediment delivery shows a sharp rise in delivery in the High Flow Reach just below the Thermalito Afterbay confluence. This is related to the increase in flow from Thermalito Afterbay and therefore an increase in erosion from the channel boundary. The net bed material yield is about 2.6 million tons after 50 years. Of this quantity, about 2.1 million tons was from bed erosion in the reach over the 50 years. The remaining 0.5 million tons was introduced load from the Low Flow Reach.
- The 25 and 50 year model runs show that the amount of sediment delivery will decrease with time. This is a result of the progressive movement of sediment downstream with no replenishment. The combination of armoring and less bed material load will result in a more stable planform, coarser bed material, and less sediment movement.

- Large changes in channel geometry occurred directly after Dam closure. Surveys by the USGS show a large increase in channel cross-section and degradation of the channel thalweg. Some of these cross-sections have increased in cross-sectional area up to 400 percent from channel bed and bank erosion. FLUVIAL-12 modeling for the 25 and 50 year periods show that this trend is continuing, but at a much slower rate. These future changes are limited by bed and bank armoring, which in turn, will reduce future bed erosion and sediment yield.

The study results will be used by other studies to help assess the project's ongoing effects on downstream water quality, aquatic and riparian resources, and protection of private lands and public trust resources. The effects of proposed resource actions, such as flow modifications, spawning gravel enhancements, and side channel development, can be modeled to determine effectiveness prior to implementation.

7.0 REFERENCES

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APPENDIX A

CHANG CONSULTING FLUVIAL-12 FINAL REPORT- "Fluvial Modeling Study of Feather River Responses to Oroville Dam and Related Issues", February 2004.

Fluvial Modeling Study of Feather River Responses to Oroville Dam and Related Issues

Prepared for
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Montgomery Watson Harza

Prepared by
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February 2004

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GLOSSARY OF TERMS

Aggradation: A rise in channel bed elevation, usually caused by sediment deposition.

Alluvial: Relating to, composed of, or found in alluvium

Bank protection: A structure placed on a riverbank to protect the bank against erosion. Such structures are usually made of riprap stones, revetments, dikes, etc.

Bed load: That part of the sediment load that travels in contact with the bed by rolling, sliding and saltation. It is also the coarser portion of the sediment load.

Channel reach: Any stretch of the channel.

Channelization: To make a channel.

Cross sections: Channel sections that are perpendicular to the flow direction that are used to define the river channel geometry for a river study.

Degradation: A lowering of the channel-bed elevation usually caused by erosion.

Drainage basin: A surface area from which rainfall drains toward a single point.

Drop structure: A rigid structure erected across a river channel through which there is a drop in channel-bed elevation.

Erodible boundary model: A model that considers the changes in channel boundary, including channel-bed scour and fill, changes in channel width and changes related to channel curvature.

Erodible bed model: A model that only considers the changes in channel-bed level by assuming that channel width does not change.

Field calibration: The correlation of modeling results using field data. It usually involves fine adjustments of certain parameters used in modeling to improve the correlation.

Flood hydrograph: A relationship showing how the flood discharge varies with time during its occurrence.

Fluvial processes: Processes that are caused by stream action, including sediment transport, flood flow, erosion, deposition, and river channel changes.

Grade control structure: A rigid structure constructed across a river channel used to stabilize the bed elevation at the location. A drop structure is also a grade control structure.

Head cutting: Channel-bed erosion occurring upstream of a sand or gravel pit or any other depression.

Model: For this study, a model is computer software developed to simulate the hydraulics of flow, sediment transport and river channel changes.

Pit capture: A stream is diverted from its normal course into a pit of lower elevation

Scour (general and local): Erosion or removal of material caused by stream action. General scour is caused by the imbalance (non-uniformity) in sediment transport along a river channel. Local scour is caused by any local obstruction to flow, such as bridge piers, abutments, tree trunks, etc.

Sediment delivery: The cumulative amount of sediment that is delivered passing a river section in a specified period of time.

Sediment transport/replenishment: Sediment transport is the movement of sediment by flow measured usually in volume or weight per unit time. Replenishment is sediment supply to make up any previous deficit.

Study channel reach: A river channel reach that is covered in a study. Such a reach is defined by a series of cross sections taken along the channel.

Suspended load: Sediment load that travels in suspension, consisting of the finer portion of the transported sediment.

Tractive force: The force exerted by the flow on the channel boundary or on any object in the river channel, usually measured in force per unit surface area.

EXECUTIVE SUMMARY

A study was made to assess the impacts of Oroville Dam on the Feather River and on its natural resources in order to develop protection, mitigation and enhancement measures. The Feather River channel covered in this study is from the Fish Barrier Dam at river mile 66.5 to the Honcut Creek confluence at river mile 44.31. Thermalito Afterbay Outlet returns flow to the river that was diverted from above the Fish Barrier Dam and enters the Feather River at river mile 58.8. The upper reach of the Feather River from the Fish Barrier Dam to the Thermalito Afterbay Outlet return is the Low Flow Reach. The reach downstream of the Thermalito Afterbay Outlet return to Honcut Creek is the High Flow Reach. Oroville Dam cuts off the supply of bed sediment to the study reach of the Feather River. The inflow from Thermalito Afterbay Outlet also carries no bed sediment.

The computer program FLUVIAL-12 was selected for the Feather River study. The combined effects of flow hydraulics, sediment transport and river channel changes are simulated for a given flow period. River channel changes simulated by the model include channel bed fill and scour (or aggradation and degradation), width variation, and changes induced by the curvature effect. While this model is for erodible channels, physical constraints, such as bank protection, grade-control structures and bedrock outcroppings, may also be specified.

Model Calibration. Major items that require calibration include the roughness coefficient, sediment transport equation, and bank erodibility factor. Channel roughness directly affects the flow velocity and water-surface profile. Roughness coefficients were selected in consideration of the original USACE data, aerial photographs and field observations. Values of the roughness coefficients vary between 0.030 and 0.045. The computed water surface profiles based on the selected roughness were compared and verified with the observed water-surface profiles given by Blodgett for three major flood discharges.

A sediment transport formula is required in mathematical modeling of an alluvial stream. The selection of the Engelund-Hansen sediment formula for the Feather River was, in part, based on the evaluation of sediment transport formulas by Brownlie and experiences from other streams in the arid west. Suspended sand transport at the Oroville gaging station was measured by the U. S. Geological Survey. Average sediment discharges were also computed using three sediment transport formulas. The results produced by the Engelund-Hansen formula are more similar with the USGS measurement.

Bank Erodibility Factor (BEF) affects the changes in channel width and lateral migration of the channel. This factor needs to be selected according to the bank material. For this objective, all cross-sectional plots based on the 1972 Blodgett data and the 1997 Corps data were reviewed and compared. The simulated results based on different values of BEF are compared with the measured changes. Based on this comparison, the BEF value is selected for the type of bank material. In selecting the Bank Erodibility Factors for the study, the characteristics of the geologic units are also considered. Details on the selection of the BEF values are described in Section 4.4.

Sediment Delivery. Sediment delivery is defined as the cumulative amount of sediment that has been delivered passing a certain channel section for a specified period of time. Spatial variations in sediment delivery are manifested as channel storage or depletion of sediment associated with stream channel changes since the sediment supply from upstream may be different from the removal. The simulated results on sediment delivery show that there is a general trend of erosion for the channel reach with local variations. More sediment will be removed from the channel boundary although sediment deposition occurs in certain short reaches, notably in gravel pits. Net erosion from this river reach has slowed down substantially as the bed becomes armored. This net erosion from the High Flow Reach is about 2.6 million tons in 50 years. The net erosion from the Low Flow Reach is about 0.4 million tons in 50 years.

Changes in Sediment Size. In the process of erosion, finer sediments are more easily removed from the channel boundary and coarser sediments are usually left behind. The selective sediment transport and removal by size, or sediment sorting, has resulted in gradual coarsening of the bed material. For the natural bed, the average median grain size for the study reach is about 23 mm. The reach-averaged median grain size for the existing armored bed is about 60 mm. The simulated median grain size after 50 years is 75 mm. This shows that the coarsening slows down with time. As the bed material of the surface layer becomes coarser, the bed becomes less mobile; less sediment is removed by erosion.

Spawning gravel was introduced into the Lower Feather River on September 1, 1982 at river mile 65.89 just below the Fish Barrier Dam. Such spawning gravel is considerably smaller in size than the armored bed material. The introduction of 3,000 cubic yards of finer material into the channel changed the composition of the bed material. The effects of sediment introduction on grain size distribution were simulated in the model. The results show median sizes of bed sediment were generally smaller after sediment introduction. But these sizes became coarser with time. The introduction of 3,000 cubic yards of spawning gravel only had limited and temporal effects on bed material composition. The effects due to sediment introduction will be directly related to the amount and size of sediment introduced.

Changes in Channel Geometry. Channel geometry changes occur due to scour and fill, which is by no means uniformly distributed across the channel width. Scour of the bed may be accompanied by scour or fill of the overbank area, or vice versa. Such complex adjustments in channel morphology directly affect the hydraulics of flow and sediment transport. *It must therefore be emphasized that fluvial simulation must be based on an erodible boundary model instead of an erodible bed model.*

Changes in channel geometry are depicted by the simulated changes in channel bed profile and the changes in channel cross section. The simulated changes have also been compared with the measured changes, which are provided by the Blodgett cross-sectional profiles of 1972 and the 1997 Corps cross-sectional profiles of 1997. The simulation is based on the 1997 Corps channel data, which is the most comprehensive river data available. Although the simulated results pertain to future channel changes, it is the working hypothesis that the trend of changes predicted for the future should also be consistent with the previous changes from 1972 to 1997.

The channel bed has become armored as a result of channel boundary scour in the last four decades. Future channel changes are limited by bed armoring. It can be seen from the results that channel changes are generally limited in magnitude. Those reaches near mining areas are subject to greater changes than other areas. Changes in channel cross section include channel bed scour and fill, changes in channel width and lateral migration at channel bends. These changes are closely inter-related as the channel adjusts in response to the reduced sediment supply.

While the alluvial bed is subject to scour and fill that is induced by the imbalance in longitudinal sediment discharge, such channel bed development may also be caused by transverse sediment movement due to channel curvature. The transverse bed slope in curved channels is related to the spiral motion or secondary currents. Because of the streamwise variation in spiral motion, uneven bed topography is usually produced, characterized by a lower bed elevation near the concave bank. The intensity of spiral motion is directly related to the discharge. Therefore, the non-uniformity in bed topography is more pronounced at high flow and it becomes partially eliminated during the subsequent low flow. This explains why an observer of the post flood channel may fail to recognize the uneven bed scour under the muddy water at high flow. If the bank protection for a stream is designed based on the simulated pattern of channel bed scour, variable toe elevations for the banks should be used to provide an effective protection.

At channel bends, the channel bed has a transverse slope. The channel bed is lower near the concave bank and higher near the convex bank. Bank protection has already been installed along the concave banks at many channel bends. With bank protection, lateral migration of the channel is constrained by the rigid structure. There are also locations along channel bends where the concave bank is not protected, and lateral migration was simulated at these locations.

Short-Term and Long-Term Changes. Short-term channel behavior was modeled using the 1997 flood; long-term changes were studied using the 50-yr flood series. The gravel bed river has non-uniform channel geometry, characterized by the riffle pool sequence. The flow velocity and sediment transport vary from riffle to pool. During low to moderate flows, the flow velocity and sediment transport are usually higher on riffles than in pools. But at high flow, the flow velocity and sediment transport are usually greater in pools than on riffles. Because of such channel morphology, the short-term channel changes are characterized by local variations. But for long-term changes, there is a clear trend of net erosion from the river reach. A river channel is always adjusting toward establishing uniformity in sediment transport. As the velocity and sediment transport reverse from riffle to pool with the discharge for short-term changes, the uniformity in sediment transport may never be attained although each river channel is constantly adjusting toward that direction. The long-term trend is continued erosion since the sediment supply is cut off.

Fluvial Modeling Study of Feather River Responses to Oroville Dam and Related Issues

1.0 INTRODUCTION

The California Department of Water Resources owns and operates Oroville Dam on the Feather River (see location map). In applying for re-licensing of the dam, it is necessary to know the impacts of Oroville Dam on the river channel and on its natural resources in order to develop protection, mitigation and enhancement measures. The Feather River is an alluvial river; it is self-regulatory in that it adjusts its characteristics in response to any change in the environment. These environmental changes may occur naturally, as in the case of climatic variation or changes in vegetative cover, or may be a result of such human activities as river training, damming, diversion, sand and gravel mining, channelization, bank protection, and bridge and highway construction. Such changes distort the natural quasi-equilibrium of a river; in the process of restoring the equilibrium, the river will adjust to the new conditions by changing its slope, roughness, bed-material size, cross-sectional shape, or meandering pattern. Within the existing constraints, any one or a combination of these characteristics may adjust as the river seeks to maintain the balance between its ability to transport and the load provided.

The Feather River channel covered in this study is from the Fish Barrier Dam at river mile 66.5 to the Honcut Creek confluence at river mile 44.3; it has a total length of about 22.2 miles. Thermalito Afterbay Outlet returns flow to the river that was diverted from above the Fish Barrier Dam and enters the Feather River at river mile 58.8. The upper reach of the Feather River from the Fish Barrier Dam to the Thermalito Afterbay Outlet return is the Low Flow Reach. The reach downstream of the Thermalito Afterbay Outlet return is the High Flow Reach. Inflow from the Thermalito Afterbay Outlet to the river channel is the only major inflow along the study river reach; it accounts for the increase in discharge from the Low Flow Reach to the High Flow Reach.

Oroville Dam cuts off the supply of bed sediment to the study reach of the Feather River. The inflow from Thermalito Afterbay Outlet also carries no bed sediment. River channel responses to this change in sediment supply are determined by modeling. Protection, mitigation and enhancement measures shall be developed and evaluated.

River channel behavior often needs to be studied for its natural state and response to human regulation. Studies of river hydraulics, sediment transport, and river channel changes may be through physical modeling, mathematical modeling, or both. Physical modeling has been relied upon traditionally for river projects, but mathematical modeling is becoming more popular as its capabilities expand rapidly. The computer program FLUVIAL-12 was selected for the Feather River study; it is a mathematical model that is formulated and developed for water and sediment routing in natural and man-made channels. The combined effects of flow hydraulics, sediment transport and river channel changes are simulated for a given flow period.

River channel changes simulated by the model include channel bed fill and scour (or aggradation and degradation), width variation, and changes in bed topography induced by the curvature effect. These inter-related changes are coupled in the model for each time step. While this model is for erodible channels, physical constraints, such as bank protection, grade-control structures and bedrock outcroppings, may also be specified. Previous applications of this model include evaluations of general scour at bridge crossings, sediment delivery, channel responses to sand and gravel mining, channelization, and damming. It has also been applied to many designs for bank protection and grade-control structures, which must extend below the potential channel bed scour and withstand the design flood.

1.1 ERODIBLE BOUNDARY MODEL VERSUS ERODIBLE BED MODEL

The FLUVIAL-12 model is an *erodible-boundary model*; it simulates inter-related changes in channel-bed profile, channel width, and bed topography induced by the channel curvature. The erodible-boundary model is different from an *erodible-bed model* in the following ways.

(1) An erodible-bed model does not simulate changes in channel width. Since changes in channel-bed profile is closely related to changes in width, these changes may not be separated.

(2) The change in bed profile in an erodible-bed model is assumed to be uniform in the erodible zone. All points adjust up and down by an equal amount during aggradation and degradation. Actual bed changes are by no means uniform and therefore an erodible-bed model may not simulate them.

(3) An erodible-bed model does not consider the channel curvature. In reality, the bed topography is highly non-uniform in a curved channel, especially during a high flow.

(4) The erodible zone needs to be specified at all cross sections in an erodible-bed model. This means the model does not provide the extent of erosion in the channel, but the user has to inform the model about the erodible part of the channel bed. The boundary of erosion is computed and provided by the FLUVIAL-12 model, this boundary changes with the discharge and time.

1.2 CLASSIFICATION OF SEDIMENT LOAD

Sediment transport is simulated using the FLUVIAL-12 model. In order to interpret simulation results, it is important to review the **Classification of Sediment Load.** There are two common classifications of the load in a stream. The first divides the load into **bed load** and **suspended load**; the second separates the load into **wash load** and **bed-material load** (or bed-sediment load). Suspended load, by definition, moves in suspension. **Wash load** refers to the finest portion of sediment, generally silt and clay that is washed through the channel, with an insignificant amount of it being found in the bed. Wash load depends on the sediment supply from the drainage basin and it is not correlated with the flow characteristics. **Bed-material load** or bed-sediment load, on the other hand, consists of particles that are generally found in the bed material. An alluvial streambed is formed during the fluvial process of sorting, through which clay and silt are removed as wash load. The discharge of wash load depends primarily on the rate of supply; it is generally not correlated with the flow characteristics. Bed-material load, on the other hand, is usually correlated with water discharge.

A sediment transport model only computes bed material load but not wash load. The transport of wash load is controlled by the supply from the watershed. Since the fines constituting the wash load do not settle in the river channel, the transport of wash load is not correlated with flow characteristics.

2.0 SEDIMENT TRANSPORT MODELING USING FLUVIAL-12

Stream channel scour consists of general scour and local scour. General scour is related to the sediment supplied to and transported out of a channel reach. Local scour, if any, is due to local obstruction to flow by a bridge pier/bent or abutment. To determine general scour, it is necessary to consider the sediment supply by flow to the channel reach and sediment removal out of the reach. Sediment delivery in a stream channel is related to the flood hydrograph, channel geometry, sediment characteristics, etc. Channel projects alter the channel-bed configuration and therefore affect sediment delivery and erosion pattern. To account for these factors, it requires mathematical simulation of the hydraulics of stream flow, sediment transport, and stream channel changes.

2.1 SEDIMENT MODEL FOR GENERAL SCOUR

The FLUVIAL-12 model (Chang, 1988) was employed for this project. For a given flood hydrograph, the model simulates spatial and temporal variations in water-surface elevation, sediment transport and stream channel changes. Scour and fill of the streambed are coupled with width variation in the prediction of stream channel changes. Computations are based on finite difference approximations to energy and mass conservation that are representative of open channel flow.

The model simulates the inter-related changes in channel-bed profile and channel width, based upon a stream's tendency to seek uniformities in sediment discharge and power expenditure. At each time step, scour and fill of the channel bed are computed based on the spatial variation in sediment discharge along the channel. Channel-bed corrections for scour and fill will reduce the non-uniformity in sediment discharge. Width changes are also made at each time step, resulting in a movement toward uniformity in power expenditure along the channel. Because the energy gradient is a measure of the power expenditure, uniformity in power expenditure also means a uniform energy gradient or linear water surface profile. A stream channel may not have a uniform power expenditure or linear water-surface profile, but it is constantly adjusting itself toward that direction.

2.2 MODELING EFFECTS OF CHANNEL CURVATURE

The study reach of the Feather River has meandering reaches and reaches that are more or less straight. Bank erosion and lateral migration are primary features that occur at meander bends; such changes are subject to the physical constraints of bank protection, bedrock, etc. The rate of bank erosion is also related to the bank erodibility factor that needs to be calibrated for each study. Bank erosion can be caused by channel widening or it may be caused by secondary flow inherent in channel bends. Simulation of curvature-induced scour and deposition is based upon the channel curvature. Major features of transverse sediment transport and changes in bed topography are described below. For a more detailed description of the modeling for lateral migration, one is referred to the book *Fluvial Processes in River Engineering* (Chang, 1988)

Sediment transport, in the presence of transverse flow, has a component in that direction. Sediment movement in the transverse direction contributes to the adjustment of transverse bed profile. In unsteady flow, the transverse bed profile varies with time, and it is constantly adjusted toward equilibrium through scour and deposition. The transverse bed load per unit channel length q_b' can be related to the streamwise transport q_b. Such a relationship by Ikeda (1982) can be written in parametric form as

$$\frac{q_b'}{q_b} = F\left(\tan\delta, \frac{\partial z}{\partial r}\right) \tag{1}$$

Where δ is the angle of deviation of bottom currents from the streamwise direction, z is the vertical coordinate, and r is the radial coordinate. The near-bed transverse velocity is a function of the curvature, and it is computed using the flow curvature.

Eq. 1 relates the direction of bed-load movement to the direction of near-bed velocity and transverse bed slope $\partial z/\partial r$. As transverse velocity starts to move sediment away from the concave bank, it creates a transverse bed slope that counters the transverse sediment movement. An equilibrium is reached, i.e., $q_b' = 0$, when the effects of these opposing tendencies are in balance. Transverse bed-profile evolution is related to the variation in bed-material load. Ikeda and Nishimura (1986) developed a method for estimating transport and diffusion of fine sediments in the transverse direction by vertical integration of suspended load over the depth. Their method for predicting the transverse bed slope is also employed in the FLUVIAL-12 model.

Changes in channel-bed elevation at a point due to transverse sediment movement are computed using the transverse continuity equation for sediment

$$\frac{\partial z}{\partial t} + \frac{1}{1-\lambda}\,\frac{1}{r}\,\frac{\partial}{\partial r}(r\, q_s') = 0 \tag{2}$$

Where t is time and λ is porosity of bed sediment. Written in finite difference form with a forward difference for q_s', this equation becomes

$$\Delta z_k = \frac{\Delta t}{1-\lambda}\,\frac{2}{r_k}\,\frac{r_{k+1}\, q'_{s\,k+1} - r_k\, q'_{s\,k}}{r_{k+1} - r_{k-1}} \tag{3}$$

Where *k* is the radial (transverse) coordinate index measured from the center of radius. Equation 3 provides the changes in channel-bed elevation for a time step due to transverse sediment movement. These transverse changes, as well as the longitudinal changes, are applied to the streambed at each time step. Bed-profile evolution is simulated by repeated iteration along successive time steps.

2.3 SEDIMENT DELIVERY

Sediment delivery is defined as the cumulative amount of sediment that has been delivered passing a certain channel section for a specified period of time, that is,

$$Y = \int_T Q_s \, dt \tag{4}$$

Where Y is sediment delivery (yield); Q_s is sediment discharge; t is time; and T is the duration. The sediment discharge Q_s pertains only to bed-material load of sand, gravel and cobble. Fine sediment of clay and silt constituting the wash load may not be computed by a sediment transport formula. Sediment delivery is widely employed by hydrologists for watershed management; it is used herein to keep track of sediment supply and removal along the channel reach.

Spatial variations in sediment delivery are manifested as channel storage or depletion of sediment associated stream channel changes since the sediment supply from upstream may be different from the removal. The spatial variation of sediment delivery depicts the erosion and deposition along a stream reach. A decreasing delivery in the downstream direction, i.e. negative gradient for the delivery-distance curve, signifies that sediment load is partially stored in the channel to result in a net deposition. On the other hand, an increasing delivery in the downstream direction (positive gradient for the delivery-distance curve) indicates sediment removal from the channel boundary or net scour. A uniform sediment delivery along the channel (horizontal curve) indicates sediment balance, i.e., zero storage or depletion. Channel reaches with net sediment storage or depletion may be designated on the basis of the gradient. From the engineering viewpoint, it is best to achieve a uniform delivery, the non-fill and non-scour condition, for dynamic equilibrium.

3.0 FEATHER RIVER MODEL DEVELOPMENT

The FLUVIAL-12 computer model has been selected for simulating river hydraulics, sediment transport, and stream channel changes of the Feather River. Input data for the river model consists of the channel geometry, flood hydrology, and bed sediment characteristics, etc. River data compilation for the Feather River is described below:

3.1 FLOW RECORDS

Discharges of flow are a required input data for river modeling studies. The USGS stream flow records from the Oroville and Gridley gaging stations are used for this study. Records from the Oroville station are for the Low Flow Reach; those from the Gridley station are for the High Flow Reach. The starting date for the records is January 1, 1967 and it extends to the present (September 30, 2002). The inflow from the Thermalito Afterbay Outlet is the difference in flow between the High and Low Flow Reaches. The peak flow of the High Flow Reach for the recorded period is 163,000 cfs that occurred on January 2, 1997. The flow records from January 1, 1967 to September 30, 2002 cover a time span of 35 years and 9 months. In simulating 50 years of river channel changes, this series is still used; it is repeated from the beginning when the end of series is reached. The Feather River is a gravel bed river, for which sediment movement does not occur during the dry season flows. For this reason, the modeling study does not cover flow periods when the discharge is lower than 1,000 cfs in the High Flow Reach.

According to the U. S. Army Corps of Engineers, the 100-yr flood discharges for the Feather River are as follows:

For the Low Flow Reach, the 100-yr flood discharge is 144,550 cfs
For the High Flow Reach above river mile 47, the 100-yr flood discharge is 150,000 cfs
For the High Flow Reach below river mile 47, the 100-yr flood discharge is 171,950 cfs

3.2 CHANNEL GEOMETRY DATA

The most complete set of cross section data is the 1997 channel data by the U. S. Army Corps of Engineers. This data set is used for the study. Additional cross sections have also been cut from the data set at locations that are coincident with the USGS study of 1972 by Blodgett and the 1994 DWR IFIM data. The additional data are cut directly from the 1997 Corps digital terrain model. In selecting the cross section locations, the following rules were applied:

(1) The1997 Corps data is the basis for the cross section data. All the cross sections in the Corps data set are used in the model. The data were edited to delete ineffective flow areas.
(2) As a general principle, an adequate number of cross sections should be used for a channel reach to define the river channel geometry. Normally, larger spacing between cross sections can be applied to a more uniform channel reach, or to a reach subject to less changes. Cross sections are more closely spaced along a reach with less uniform channel geometry or along a reach subject to greater potential changes. In finite difference modeling scheme, the use of very small spacing between two cross sections requires large computing time; therefore, it needs to be avoided.
(3) For this study, additional cross sections were inserted into the Corps data set. The inserted sections are to achieve improved definition of the channel geometry. Such sections are located between two Corps sections, preferably near the center point between the two sections. The 1997 two-foot contour topography was used to generate such cross sectional data.
(4) Many of the inserted cross sections are at the Blodgett section locations. Changes at these cross sections that occurred in the 25-yr time span from October 1, 1972 to September 30, 1997 are useful for model calibration. In order to maintain an

adequate spacing between two adjacent cross sections, a Blodgett section location that is very close to one section but far from the other section is not selected.

These cross-sectional data have been edited to specify the effective flow areas and to exclude ineffective flow areas. The radii of curvature that are measured directly from the work map specify channel curvature.

3.3 GRAVEL MINING AND SIDE FLOW WEIRS

Gravel mining occurred in and along the main channel of the Feather River. Instream mining area is near river mile 61. Major offstream mining pits are scattered along the channel reach. Huge gravel pits have been created due to mining. These mining sites are shown in the accompanying maps. River flow may spill into the borrow sites through the side flow weirs under certain flow conditions.

There exist four side-flow weirs; two of them are along the High Flow Reach and the other two are along the Low Flow Reach. Their respective locations and characteristics are listed in Table 1. In setting up and calibrating the FLUVIAL-12 model, one of the items considered is whether or not the side flow weirs of the four borrow areas have a significant impact on altering flows related to the sediment transport model.

Table 1. Summary of Side Flow Weirs

WEIR	LOCATION RIVER MILES	CREST ELEVATION FEET	WEIR LENGTH FEET
A	62.4	135.5	460
B	59.6	122.5	370
C	56.5	109.0	480
D	55.0	106.0	290

To help address whether the four weirs have a significant impact on discharge in the Feather River channel, some estimates were made to determine their effects. How the river and borrow area water levels relate to each other is not known so assumptions were made to try to determine whether or not the weir flows need to be accounted for in the FLUVIAL-12 model. The primary assumptions relate to the methods used to calculate the water storage capacity of the borrow areas.

First, the surface area was determined by delineating each borrow area on a contour map. The side slopes of the borrow ponds were neglected and assumed to be vertical. In addition, it was assumed that the borrow pits were flat and empty. Mining tailings do exist within the borrow areas, but to be conservative these were ignored. Volumes were then calculated from the lowest elevation of the borrow areas to the weir inverts. It was also assumed that the borrow areas would be empty in estimating the time it would take to fill them at different weir flow rates. This is an unlikely scenario, but without reliable data to make a reasonable estimate of what the borrow area capacities would be, the worst case scenario was used. The attributes of the four borrow areas are listed in Table 2 and the time to fill the borrow area for different depths and weir flows were estimated as summarized in Table 3.

Table 2. Borrow Area Dimensions

Borrow Area Dimensions				
	Borrow Area A	**Borrow Area B**	**Borrow Area C**	**Borrow Area D**
Surface Area (acres)	1028	345	1653	564
Full Depth Volume to weir invert (acre-feet)	8208	3101	14854	5628
Depth to weir invert (feet)	8	9	9	10
Weir Length (feet)	460	370	480	290

Table 3. Computed Weir Flows at Various Depths over Weir

2 Feet of Weir Depth				
	Borrow Area A	**Borrow Area B**	**Borrow Area C**	**Borrow Area D**
River Flow (cfs)	85000	85000	53000	53000
Weir Flow (cfs)	3422	2752	3571	2157
% of Weir to River Flow	4.0%	3.2%	6.7%	4.1%
Time to Fill (hours)	29.0	13.6	50.3	31.6

4 Feet of Weir Depth

	Borrow Area A	Borrow Area B	Borrow Area C	Borrow Area D
River Flow (cfs)	9000	99000	105000	122000
Weir Flow (cfs)	9678	7785	10099	6102
% of Weir to River Flow	9.8%	7.9%	9.6%	5.0%
Time to Fill (hours)	10.3	4.8	17.8	11.2

6 Feet of Weir Depth				
	Borrow Area A	Borrow Area B	Borrow Area C	Borrow Area D
River Flow (cfs)	113500	113500	130250	156000
Weir Flow (cfs)	17780	14302	18553	11209
% of Weir to River Flow	15.7%	12.6%	14.2%	7.2%
Time to Fill (hours)	5.6	2.6	9.7	6.1

8 Feet of Weir Depth			
	Borrow Area A	Borrow Area B	Borrow Area C
River Flow (cfs)	128000	128000	156000
Weir Flow (cfs)	27375	22019	28565
% of Weir to River Flow	21.4%	17.2%	18.3%
Time to Fill (hours)	3.6	1.7	6.3

10 Feet of Weir Depth		
	Borrow Area A	Borrow Area B
River Flow (cfs)	142000	142000
Weir Flow (cfs)	38257	30772
% of Weir to		

River Flow	26.9%	21.7%
Time to Fill (hours)	2.6	1.2

Since average daily flows are used in the FLUVIAL-12 model, any effects of the borrow areas filling that last under a one day period is negligible. In coming up with these estimates, it should be remembered that most of the assumptions were conservative and that the time estimates are very likely longer than what would actually occur. Based on these estimates, it is concluded that the weirs do not have a significant impact on discharge in the Feather River. The estimates show that the borrow areas would be filled with water to the weir invert elevations in a matter of hours. Since average daily flows are used in the FLUVIAL-12 model, the effects would not be seen.

3.4 GEOLOGIC AND BED SEDIMENT DATA

River channel changes consist of riverbed scour and fill, changes in channel width and lateral migration. The bank material affects changes in width and lateral migration. Detailed geologic information of the river channel and the bank areas have been obtained and used in the data set. More on this subject is described later in the report.

Samples of bed sediment were collected from the surface layer and the subsurface layer along the river reach. Sieve analyses were made to obtain the grain size distributions. The grain size distributions are used in the modeling study. In general, grain size distributions for the surface layer of the channel bed are used. It is evident from these grain size distributions that the study reach of the Feather River is basically a gravel-bed river. The channel bed has become armored as a result of scour development in the last few decades. Armoring is due to the lack of sediment supply and selective transport of sediment by size. As bed sediment is removed by flow from the channel bed, finer particles tend to be removed first, leaving coarser particles behind to form an armored layer.

3.5 PHYSICAL CONSTRAINTS

River channel changes are constrained by rigid channel boundaries, such as bank protection, bedrock, hardpan, grade control structures, check dams, levees, etc. Locations of such physical constraints were entered in the input data.

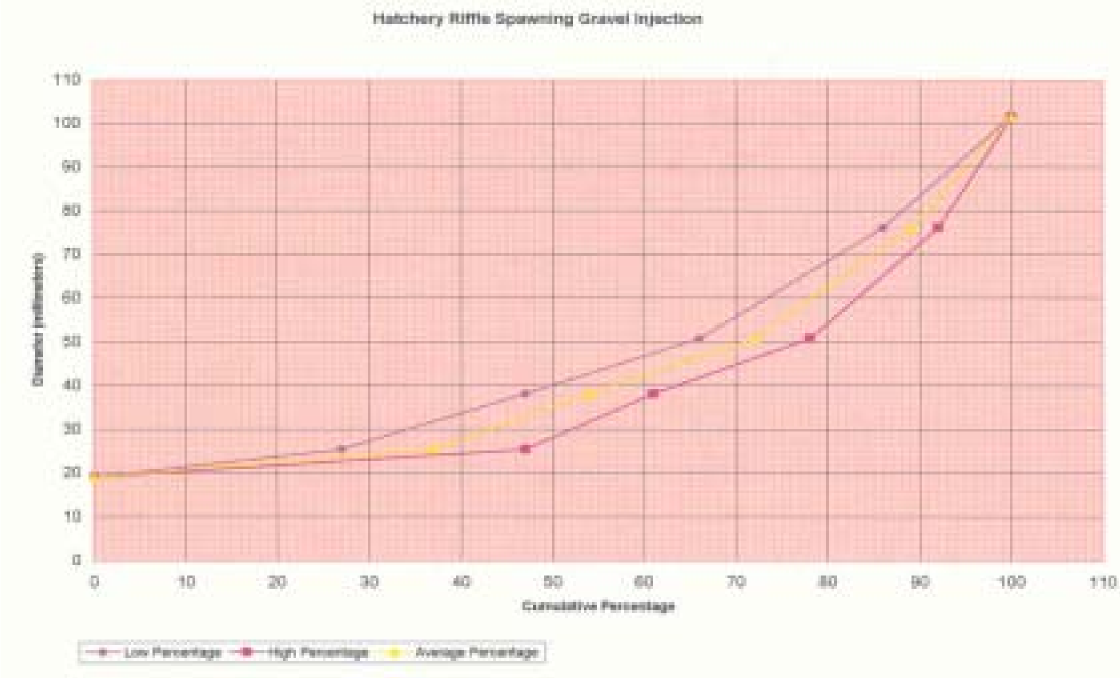

Fig. 1. Grain size distribution of spawning gravel used in feeding

3.6 SEDIMENT INTRODUCTION INTO THE RIVER CHANNEL

Spawning gravel was introduced into the Lower Feather River on September 1, 1982, at river mile 65.89 just below the Fish Barrier Dam. Grain size distribution of the spawning gravel is shown in Fig. 1. Such gravel has a median diameter of 35 mm, which is considerably finer than the median grain size of 120 mm for the surface layer. The total amount of sediment introduced was 3,000 cubic yards. This information was included as a part of the input data in the modeling study; the results will also be discussed in a later section.

4.0 MODEL CALIBRATION

The accuracy of a mathematical model depends on the physical foundation, numerical techniques, and physical relations for momentum, flow resistance, and sediment transport. Test and calibration are important steps to be taken for the more effective use of a model. Because of the difference in sensitivity of simulated results to each relation or empirical coefficient, more attention needs to be paid to those that generate sensitive results. Major items that require calibration include the roughness coefficient, sediment transport equation, and bank erodibility factor.

To determine the sensitivity of flow, sediment transport, and channel changes caused by the variation of each variable, different values of the variable need to be used in simulation runs, and the results so obtained are compared. Generally speaking, the rate of channel changes is more sensitive to the sediment rate computed from a sediment equation, but the equilibrium channel configuration is less sensitive. For example, the constriction scour at a bridge crossing, or the equilibrium local scour at a bridge pier, is found to be more or less independent of the sediment equation, or sediment size, since both inflow and outflow rates of sediment are affected by about the same proportion. It may also be stated that the rate of widening is sensitive to the bank erodibility factor but that the equilibrium width is not nearly as sensitive.

Field data are generally used for test and calibration of a model. The required information includes channel configuration before and after the changes, a flow record, sediment characteristics, and sediment records, etc. Data sets with more complete information are also more useful. The FLUVIAL-12 has undergone test and calibration using many data sets. Many such data sets are also useful for the test and calibration of other models. Previous calibration studies for rivers in northern California are listed below, including a previous study of the Feather River above Oroville Dam.

(1) Test and Calibration Study Using Data from the San Lorenzo River in Northern California. Chang, H. H., 1985, "Water and Sediment Routing through Curved Channels", *Journal of Hydraulic Engineering*, ASCE, 111(4), 644-658.

(2) Test and Calibration Study Using Data from Stony Creek in Northern California. Chang, H. H., Harris, C., Lindsay, W., Nakao, S. S., and Kia, R., 1993, "Selecting Sediment Transport Equation for Scour Simulation at Bridge Crossing", *Proceedings* of the 1993 National Conference on Hydraulic Engineering, San Francisco, CA, July 25-30, pp. 1744-1949. Chang, H. H., 1994, "Selection of Gravel-Transport Formula for Stream Modeling", *Journal of Hydraulic Engineering*, ASCE, Vol. 120, No. 5, May, pp. 646-651.

(3) Test and Calibration Study Using Data from the Feather River in Northern California. Chang, H. H., 1993, "Numerical Modeling for Sediment-Pass-Through Operations of Reservoirs on North Fork Feather River", prepared for Pacific Gas & Electric Company, San Francisco. Chang, H. H., Harrison, L., Lee, W., and Tu, S., 1996, "Numerical Modeling for Sediment-Pass-Through Reservoirs", *Journal of Hydraulic Engineering*, ASCE, Vol. 122, No. 7, pp. 381-388.

4.1 SELECTION OF CHANNEL ROUGHNESS COEFFICIENTS

Channel roughness is specified by the roughness coefficients; it directly affects the river stage and flow velocity, and indirectly affects sediment transport and channel changes. The river stage changes in direct relation to channel roughness while the velocity is inversely related to roughness. In ordinary practice, the modeler selects the roughness coefficients following guidelines given in manuals or standard textbooks. It is also desirable to calibrate the roughness coefficients if measured river stage and velocity are available.

Roughness coefficients for this study were selected in consideration of the Corps data and field observations that are described below. Channel roughness data for the 1997 Corps study was reviewed, together with aerial photographs of the river channel. Roughness coefficients were then selected in consideration of the Corps data, aerial photographs and field observations. Values of the roughness coefficients vary between 0.030 and 0.045.

Observed water-surface elevations are given in the Blodgett report for the floods of December 23, 1964 and January 25-27, 1970. The December 23, 1964 flood has the discharge of 156,000 cfs; the January 25-27, 1997 flood has the average discharge of 71,000 cfs for the High Flow Reach and 53,000 cfs for the Low Flow Reach. The difference in discharge is due to inflow from the Thermalito Afterbay Outlet. The Blodgett report also provides the water-surface profile for the discharge of 150,000 cfs.

Figures 2, 3 and 4 show channel-bed profiles of the river reach from the 1972 Blodgett survey and the 1997 Corps survey. It can be seen that the channel bed changed from 1972 to 1997. Changes are related to both natural causes and human activities. It can be seen that there is a general degradation trend from 1972 to 1997, except that the channel bed between river mile 54 and 58 has aggraded. The instream mining near river mile 61 enlarged the channel width.

The water-surface profile is also computed using FLUVIAL-12 for various flood discharges based on the 1997 channel geometry. The computed water-surface profile reflects the effects of selected roughness coefficients. The computed water-surface profile is compared with the observed water surface profile for the 1964 flood as shown in Fig. 2. Comparisons of computed and observed water-surface profiles for the 1970 flood and the discharge of 150,000 cfs are shown in Figs. 3 and 4, respectively. The computed and observed water-surface profiles for all three cases are generally similar. The differences are related to the natural changes in channel geometry and instream mining activities. They are also related to any imprecision in selected roughness coefficients. The mining operation near river mile 61 enlarged the channel width and it contributes to a lower water surface profile.

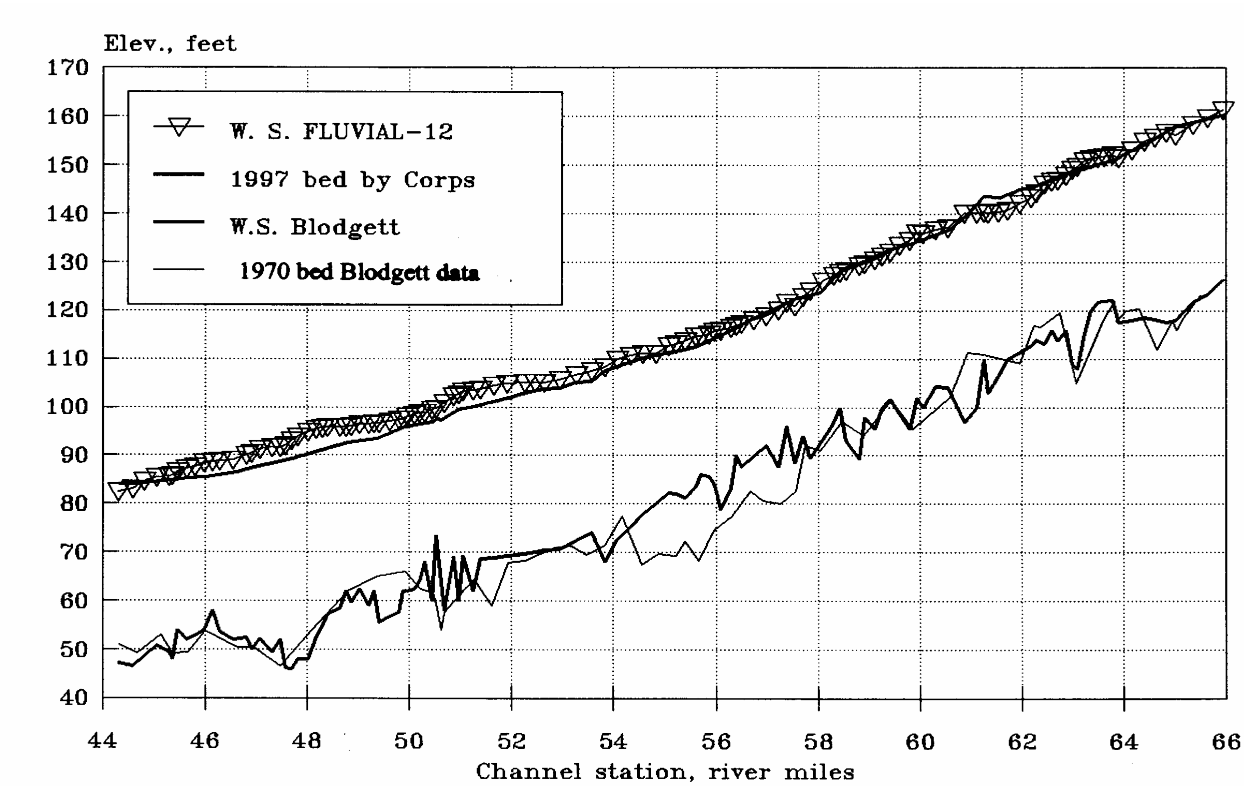

Fig. 2. Comparison of computed and observed water-surface profiles based on December 23, 1964 flood (Q=156,000 cfs)

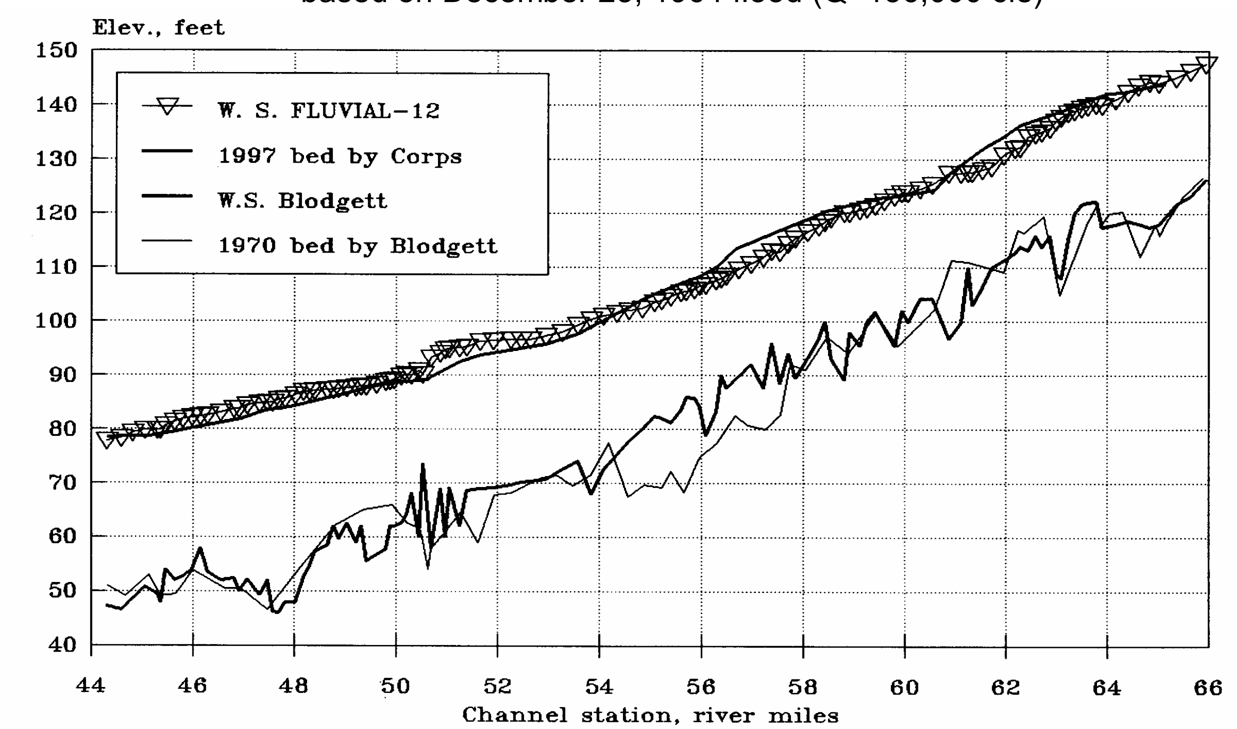

Fig. 3. Comparison of computed and observed water-surface profiles based on January 25, 1970 flood (Q=71,000/53,000 cfs)

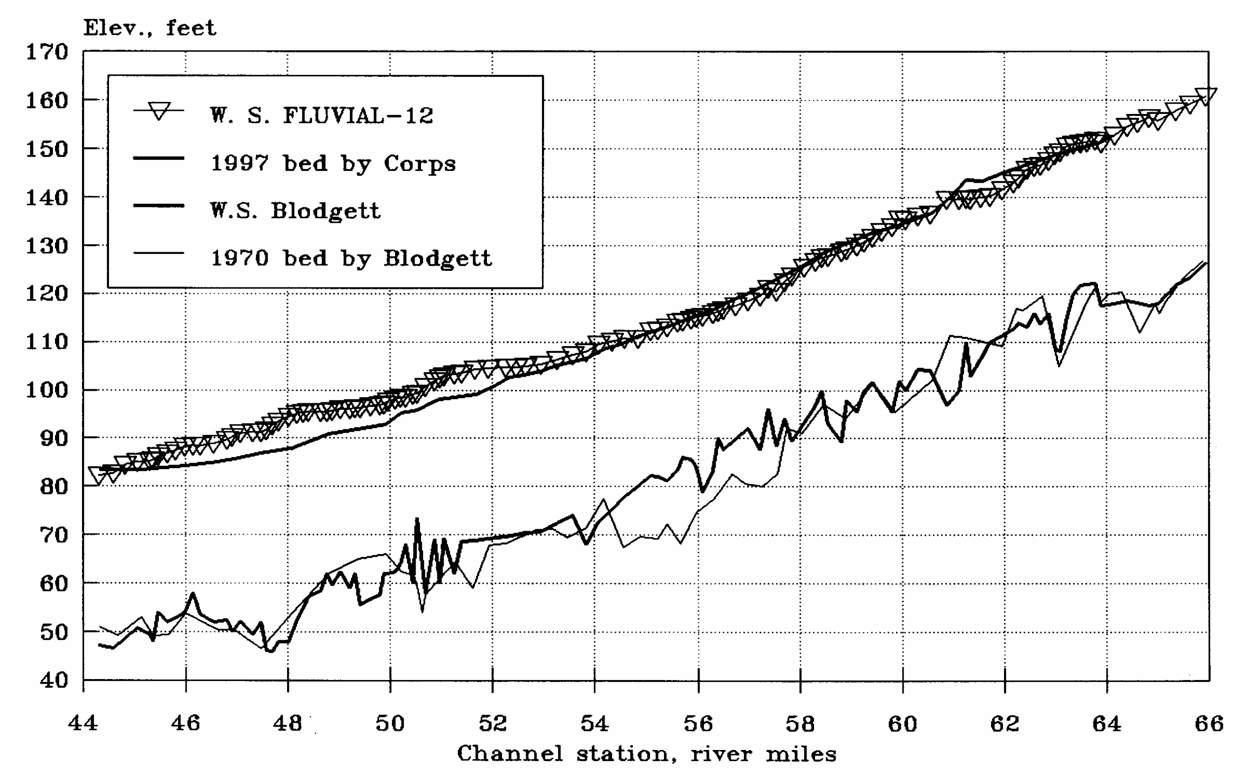

Fig. 4. Comparison of computed and observed water-surface profiles based on the discharge of 150,000 cfs

In addition to the water-surface profiles, Figs. 2, 3, and 4 also show the comparison of channel-bed profiles based on the Blodgett data of 1972 and the Corps data of 1997. The channel bed profile is the profile of the thalweg (minimum bed elevation). It is not a good indication of channel bed aggradation and degradation as explained below. Changes at a cross section due to scour or fill is by no means uniformly distributed across the bed width. In some case, the thalweg may undergo scour (degradation) but the adjacent bed areas may have fill (aggradation), and vice versa. The net change in cross-sectional area at a cross section cannot be determined based on the changes in channel-bed profile alone. One must also consider the overall changes in cross-sectional profile.

4.2 SIDE FLOW WEIRS

There exist four side-flow weirs; two of them are along the High Flow Reach and the other two are along the Low Flow Reach. Their respective locations and characteristics are listed in Table 1. The January 25, 1970 flood had the discharge of 71,000 cfs for the High Flow Reach and 53,000 for the Low Flow Reach. Water-surface profile for this discharge was computed based on the1997 cross-sectional data. The computed elevations at the weirs are listed below:

At river mile 62.4: 133.0
At river mile 59.6: 122.5
At river mile 56.5: 109.0
At river mile: 55.0: 105.0

The peak water-surface elevations during the 1970 flood are shown in Fig. 3; they are closely similar to the respective weir crest elevations. For this reason, flow through the weirs only occurs when the flood discharge exceeds about 71,000 and 53,000 cfs for the high flow and Low Flow Reaches, respectively. According to stream flow records; there were a few major flood events with discharges higher than 71,000/53,000 cfs. During such events, floodwater overflowed the weirs into the adjacent borrow sites. Flow leaving the channel through the weirs affects the discharge in the channel. This change in channel discharge may need to be taken into account. An analysis of the weir flow effects on channel flow is given below.

First of all, the weirs are located along the Feather River bank downstream of the Oroville gaging station and upstream of the Gridley station. The flow records from the Oroville station are used for the Low Flow Reach and those from the Gridley station are used for the High Flow Reach. Since the Oroville station is located upstream of the weirs, the flow records do not reflect the effects of the weirs. The Feather River near Gridley station is located downstream of all weirs, its records reflect the effects of the weirs. At discharges higher than 71,000 cfs, the flow discharge along the High Flow Reach with weirs can be different from the discharge at the Gridley station. To assess the weir effects on flow, the measured flow from the Oroville station is combined with the Thermalito Afterbay outflow. The weirs do not affect the combined flow whereas the weirs affect the Gridley flow. The hydrograph of the combined flow is shown in Fig. 5 together with the flood hydrograph measured at the Gridley station. It can be seen that these two hydrographs are closely similar. The Gridley flow discharges are not lower than the corresponding combined flow discharges. From this comparison, it may be concluded that the discharge of major floods recorded at the Gridley station is not significantly altered by weir flows. The stream gaging records can be used without modifications.

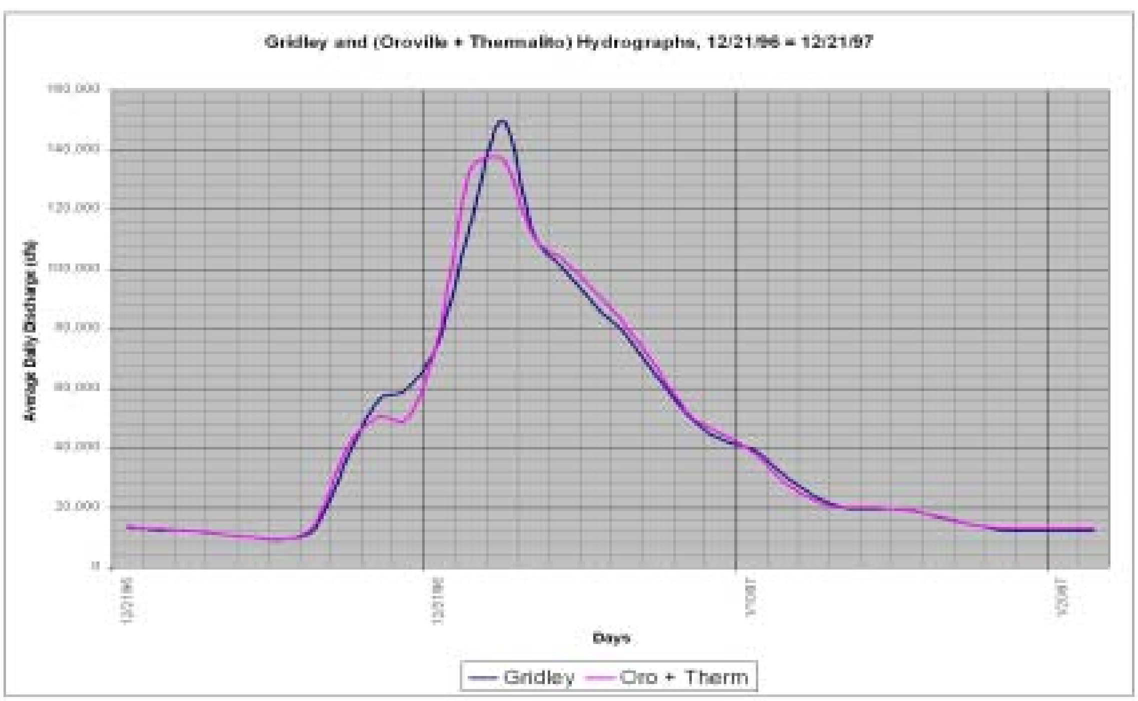

Fig. 5. Hydrograph for the 1997 flood from the Gridley station compared with combined flows from the Oroville station and Thermalito Afterbay Outlet return flow

4.3 SELECTION OF A SEDIMENT TRANSPORT FORMULA FOR THE STUDY

A sediment transport formula is required in mathematical modeling of an alluvial stream. Several comparisons of accuracy for different formulas have been made, such as those by ASCE (1975), Alonso (1980), and Brownlie (1981). The comparison of 14 formulas by Brownlie (1981) is shown in Fig. 6. The bars show the 16th and 84th percentile of the values of the predicted-concentration--measured-concentration ratio for flume data (solid lines) and field data (dashed lines). The median value is indicated by x. Although Brownlie's formula rates very well in the comparison, it is cautioned that the coefficients in this formula were determined from the data used in the figure. One of the major problems on the rating of sediment transport formulas stems from the fact that similar data sets were used by different workers in developing their respective formulas. The selection of the Engelund-Hansen sediment formula for the Feather River was, in part, based on the evaluation of sediment transport formulas by Brownlie and experiences from other streams in the arid west.

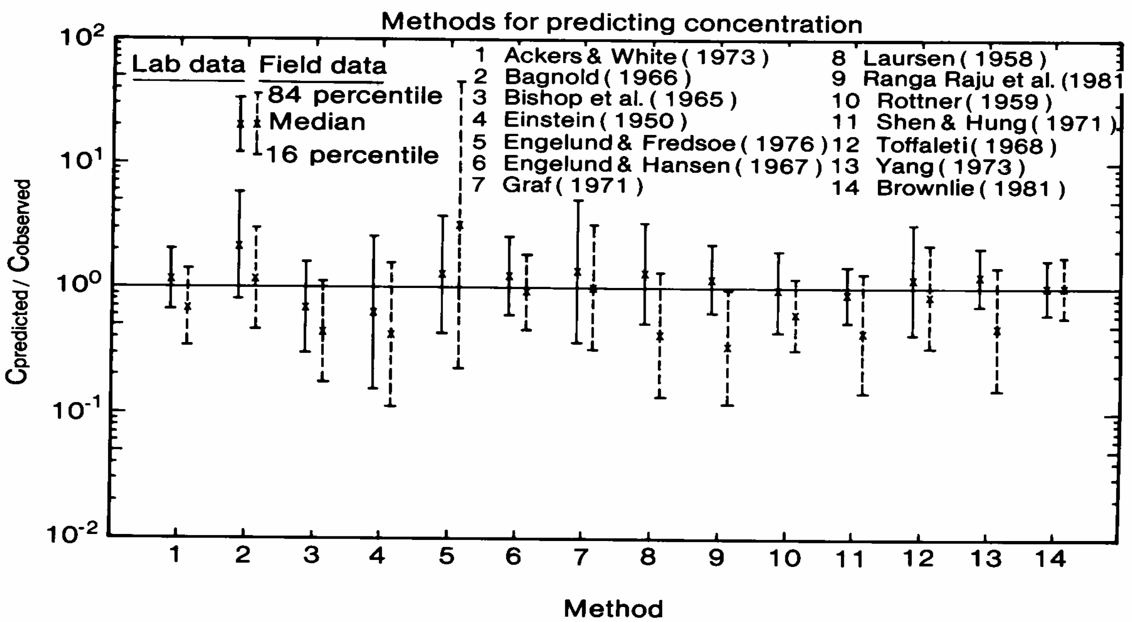

Fig. 6. Comparison of methods for predicting sediment concentration. Median and 16th and 84th percentile values are based on the approximation of a lognormal distribution of errors (Brownlie, 1981).

4.3.1 Comparison with Sediment Measurement—A sediment study of the Feather River is documented in the report "Sediment Transport in the Feather River, Lake Oroville to Yuba City, California', by the U. S Geological Survey in 1978. Sediment transport at the Oroville gaging station is given in relation to the flow discharge. The rating curve for suspended sand is shown in Figs. 7 and 8. The measurements used to establish the rating curve were made in the 1968-75 water years after the completion of Oroville Dam.

Average sediment discharges were also computed for the low reach using the three following sediment transport formulas: (1) Parker formula for bed load, (2) Ackers-White formula for bed-material load, and (3) Engelund-Hansen formula for bed material load. The results are described below:

The bed load computed using the Parker formula has the value of zero for the range of water discharges used. This is not surprising since the Parker formula is a bed load formula and most of the sediment load moves in suspension. Bed load that moves in contact with the bed has a much smaller speed and it is a small portion of the bed material load. The bed material load molds channel geometry. Since the Parker formula does not simulate the suspended portion of the bed material load, it may not be employed for this study.

The sediment discharge versus water discharge relation computed using the Ackers-White formula is shown in Fig. 7. The relation using the Engelund-Hansen formula is shown in Fig. 8. From these figures, it is easy to see that the results produced by the Engelund-Hansen formula are more similar with the USGS measurement. However, it should be noted that the USGS measurement occurred in the 1968-75 period. The computation is based on the current bed material composition. The channel bed has become coarser and even more armored since 1975.

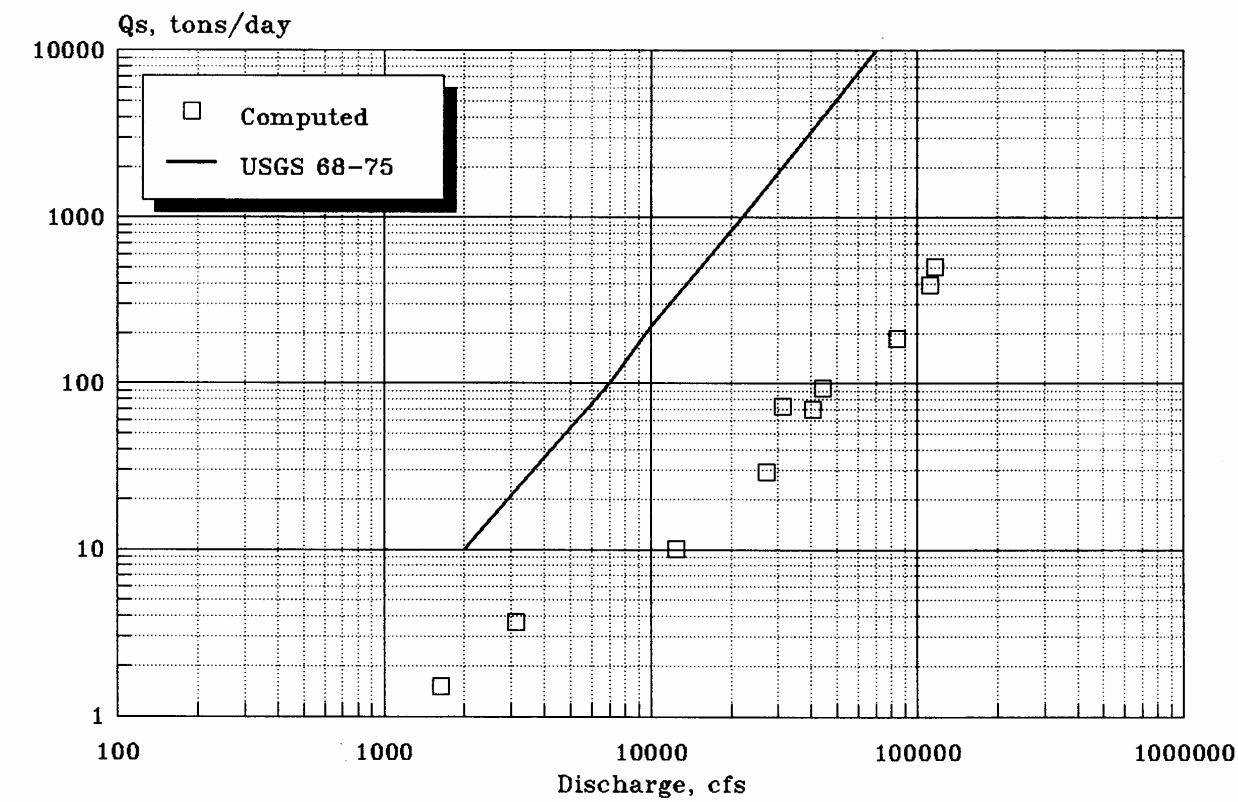

Fig. 7. Rating curves for sediment transport based on Ackers-White formula and USGS measurement

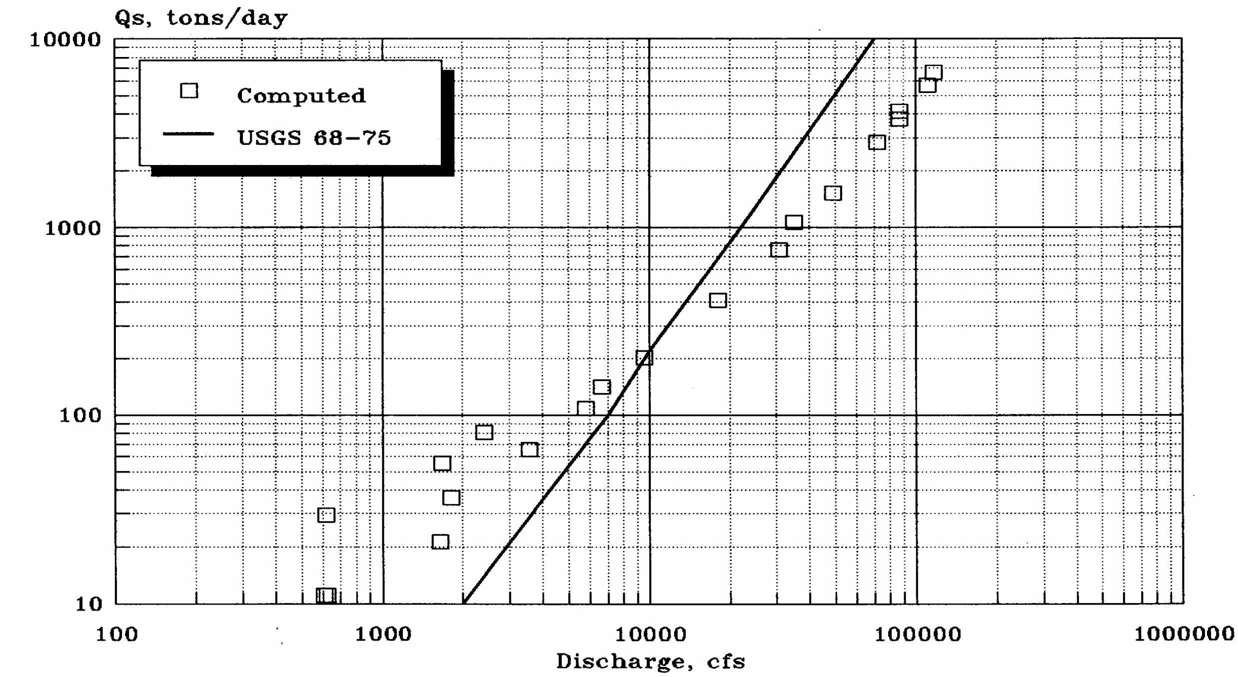

Fig. 8. Rating curves for sediment transport based on Engelund-Hansen formula and USGS measurement

4.4 BANK ERODIBILITY FACTOR

Bank Erodibility Factor (BEF) affects the changes in channel width and lateral migration of the channel. This factor needs to be selected to reflect the variation in bank material. One of the objectives of the calibration study is to determine the BEF for the river channel. For this objective, all cross-sectional plots based on the 1972 Blodgett data and the 1997 Corps data were reviewed. Cross sections at the same locations from these two data sets are plotted on the same sheet. By comparing the cross-sectional geometries of 1972 and 1997, it can be seen that changes along the river bank is the most pronounced at the concave bank of the river bend if the bend is not protected by riprap. Such is the case for section 61.95 in the Low Flow Reach. The concave bank at this location has retreated from 1972 to 1997 as much as 100 feet. This is the only location along the Low Flow Reach with a substantial natural change in bank line during this period.

Bank Erodibility Factor for the channel is a measure of bank erosion in relation to channel bed erosion. For a sand bed channel, the value of BEF is typically less than one since bank erosion is inhibited by natural vegetation and cohesive soil whereas the bed is usually not. For a gravel bed river, such as the Feather River, the channel bed is armored, and therefore resistant to erosion, the value of BEF can exceed 1 since the bank can be more erodible than the bed.

The flood series from 1972 to 1997 was used to simulate channel changes based on the cross-sectional data for existing conditions. In order to determine the effects of BEF on bank retreat, three BEF's were used; these are 0.3, 0.5, and 0.8. Simulated changes for the respective BEF's are plotted as shown in Figs. 9, 10 and 11. It can be seen from the plotted results that bank erosion is directly related to the value of BEF. A higher BEF value also produces more bank erosion.

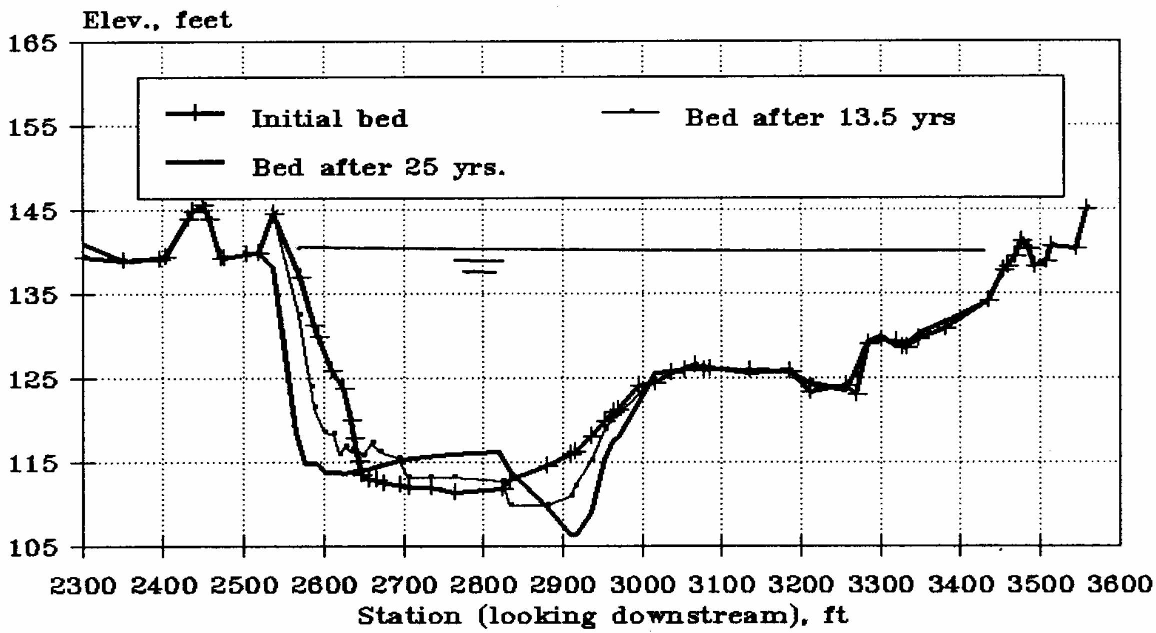

Fig. 9. Lateral migration at channel bend based on BEF of 0.3

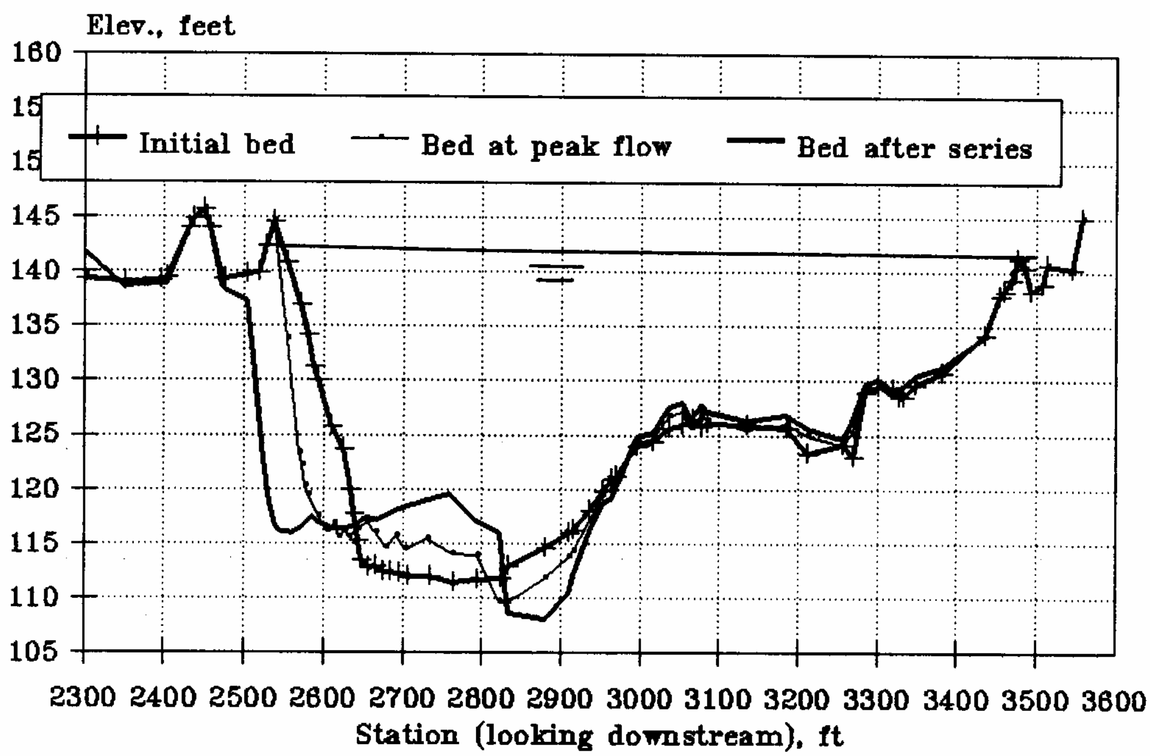

Fig. 10. Lateral migration at channel bend based on BEF of 0.5

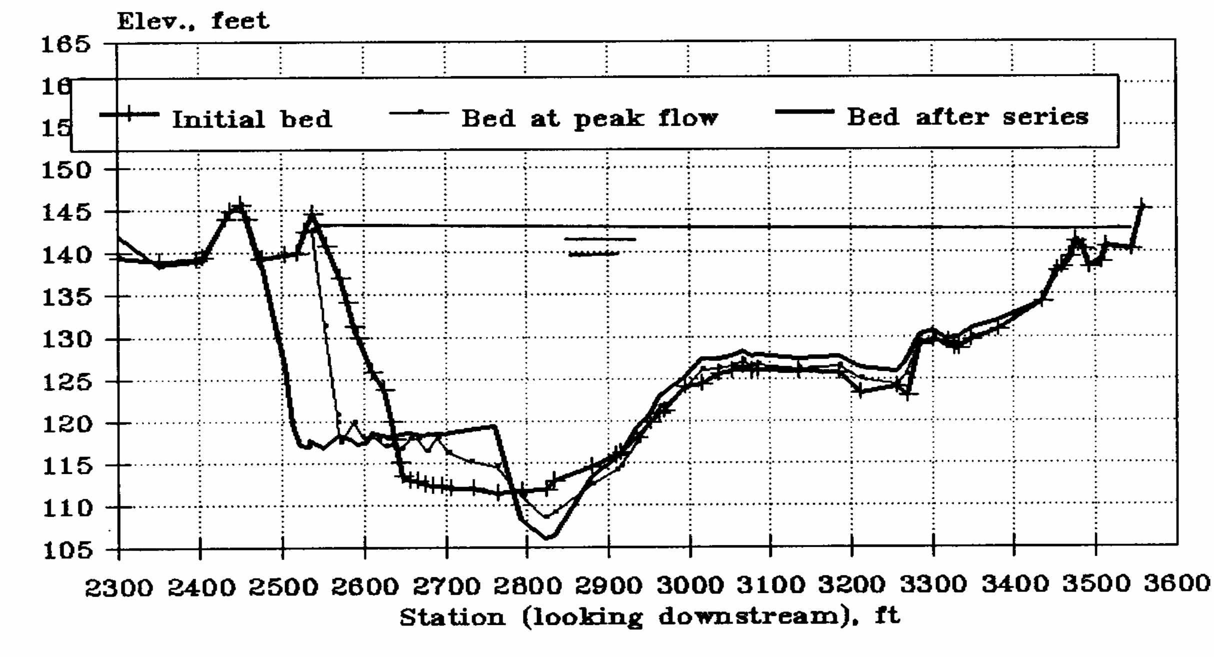

Fig. 11. Lateral migration at channel bend based on BEF of 0.8

Measured changes at this location are shown in Fig. 12. The simulated results are compared with the measurement. Bank retreat is under-predicted by the BEF value of 0.3, but is over-predicted by the BEF value of 0.8. Based on this comparison, the BEF value of 0.5 is selected for this channel reach. In selecting the Bank Erodibility Factors for the study, the characteristics of the geologic units are also considered. The selected values for BEF's are listed in Table 4.

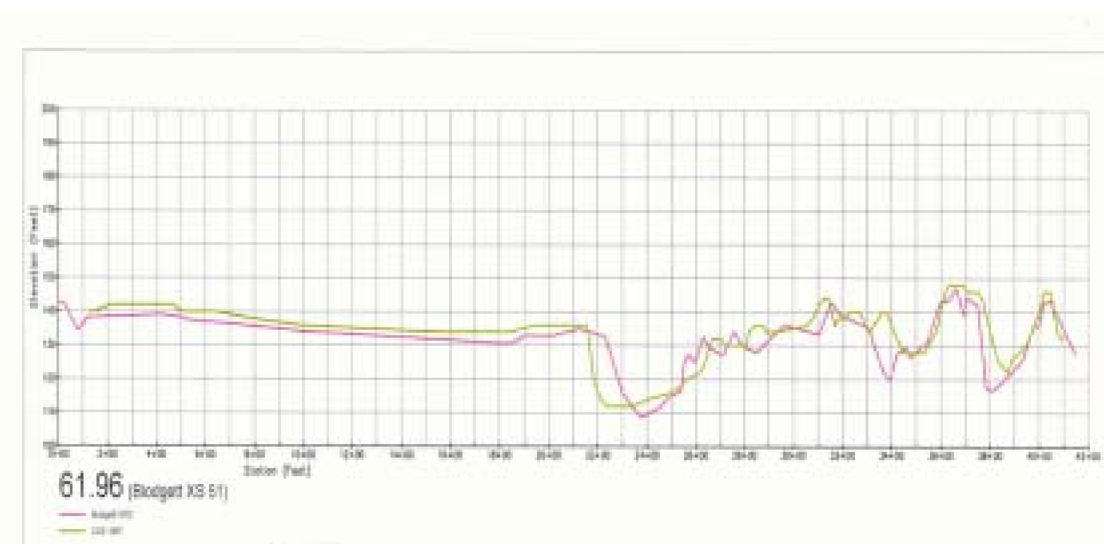

Fig. 12. Measured channel changes from 1972 (Blodgett data) to 1997 (Corps data)

Table 4. Summary of Bank Erodibility Factors

GEOLOGIC UNIT	DESCRIPTION OF EROSION	ESTIMATED EROSION RATE (FEET /100 YRS.)	BANK ERODIBLITY
Composite silt/Gravel Banks	Highly erodible	100 to 1,000	0.5
Gravel bank	Highly erodible	100 to 1,000	0.5
Cobbles or Tailings	Moderately erodible	50 to 100	0.2
Clays from hydraulic mining	Moderately erodible	50 to 100	0.2
Modesto Formation	Moderately erodible	50 to 100	0.2
Riverbank Formation	Somewhat erodible	10 to 50	0.1 to 0.2
Laguna Formation	Slightly erodible	1 to 10	0.01 to 0.1
Ione Formation	Slightly erodible	1 to 10	0.01 to 0.1
Chico Formation	Slightly erodible	1 to 10	0.01 to 0.1
Mariposa/Logtown Ridge Formation	Non-erodible	0 to 1	0.0
Jurassic bedrock	Non-erodible	0 to 1	0.0

4.5 INITIATION OF SEDIMENT MOTION

Flow conditions for the initiation of sediment motion were determined for different gravel sizes. The most commonly used criterion for the initiation of sediment motion is the Shields criterion (see Chang, 1988). For river flow in the rough zone, the Shields criterion for incipient motion is as follows.

$$\frac{\tau_c}{(\gamma_s - \gamma)\, d} = 0.06 \qquad (5)$$

In the equation, τ_c is the critical shear stress for incipient motion, in pounds per square foot; γ_s is the unit weight of sediment (165 lbs/ft^3); γ is the unit weight of water (62.4 lbs/ft^3); and d is the sediment size (feet). The above equation can be written as:

$$\tau_c = (165–62.4)0.06\ d = 6.156d$$

and $\quad d\ (\text{feet}) = 0.162\ \tau_c$

or $\quad d\ (\text{inches}) = 1.95\ \tau_c\ . \qquad (6)$

Therefore, the critical shear for gravel is directly proportional to the effective gravel size.

The shear stress at a point in channel bed is computed by

$$\tau_c = \gamma y S \tag{7}$$

where y is the depth of flow and S is the energy slope.

The Feather River has gradually-varied flow over riffles and pools at all times. The channel bed shear stress varies from cross section to cross section. At the same cross section, the shear stress also varies from point to point. Usually, the maximum shear stress occurs at the thalweg. Therefore, incipient motion usually starts from the thalweg. Because of the variation in flow characteristics, the sediment motion occurs at certain bed locations but not at other locations. For the present study, the average flow condition of a channel reach for the initiation of sediment motion is considered. Under this condition, about half of the cross sections have little or no sediment motion, but the other half still have limited sediment motion.

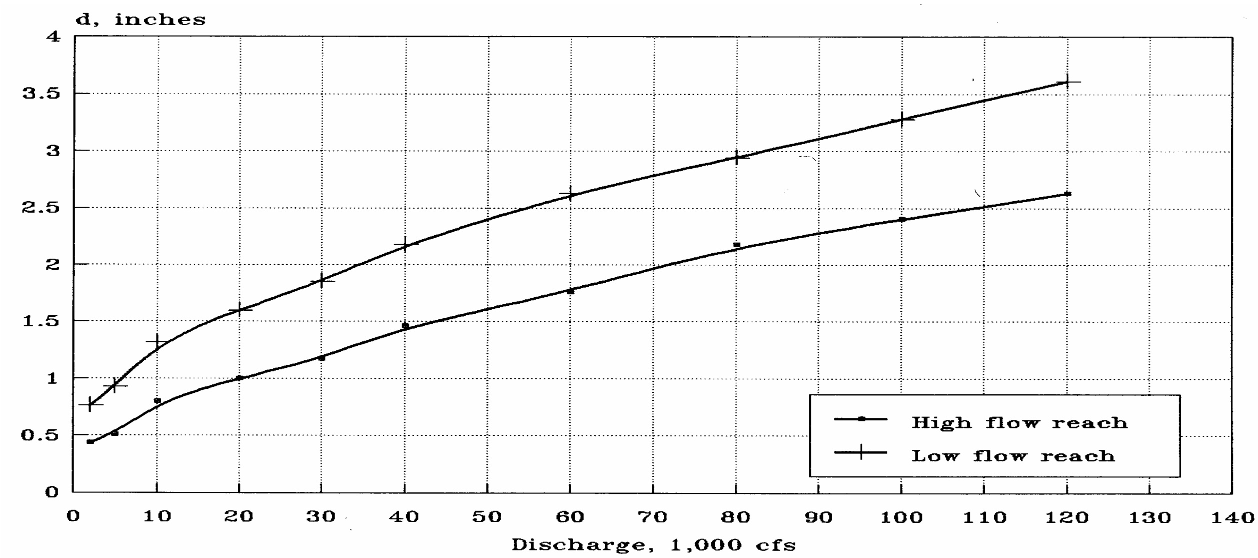

Fig. 13. Sediment grain size in relation to flow discharge at initiation of motion

Table 5 lists several discharges, their respective flow depths and shear stresses at the thalweg for the High Flow Reach and the Low Flow Reach. The shear stress is computed using Eq. 7. The grain size of gravel for the shear stress to cause incipient motion is computed based on Eq. 6. Sediment grain size in relation to flow discharge at initiation of motion is shown in Fig. 13. The figure shows that in the Low Flow Reach, incipient motion of the 2-inch gravel occurs at the discharge of 35,000 cfs; and the motion of 3.5-inch gravel is initiated at the discharge of 114,000 cfs. In the High Flow Reach, incipient motion of the 2-inch gravel occurs at the discharge of 72,000 cfs; the 3.5-inch gravel does not move at the discharge of 114,000 cfs. The High Flow Reach has a flatter slope than the Low Flow Reach; it takes more flow to move the same size gravel in the High Flow Reach than in the Low Flow Reach.

Table 5. Summary of Sediment Load in Relation to Flow Discharge
Slope of High Flow Reach = 0.0006
Slope of Low Flow Reach = 0.0009

DISCHARGE CFS	AVERAGE FLOW DEPTH OF THALWEG FT		AVERAGE SHEAR STRESS OF THALWEG LBS/FT^2	
	High Flow Reach	Low Flow Reach	High Flow Reach	Low Flow Reach
2,000	6	7	0.23	0.39
5,000	7	8	0.26	0.45
10,000	11	12	0.41	0.67
20,000	14	15	0.52	0.84
30,000	16	17	0.60	0.95
40,000	20	20	0.74	1.12
60,000	24	24	0.90	1.35
80,000	30	27	1.12	1.51
100,000	33	30	1.23	1.68
120,000	36	33	1.35	1.85

4.6 MODELED RESULTS FOR 25-YR CALIBRATION FLOOD SERIES

There exist two sets of measurements for the cross-sectional geometry of the Feather River: These are the 1972 data by Blodgett and the 1997 data by the Corps of Engineers. Cross sections were cut at the locations of the Blodgett study based on the USCOE digital terrain model. Simulated river channel changes from 1972 to 1997 can be compared with the measured changes in order to assess the validity of the modeling method. While many cross sections in these data sets are not at the same location, the general pattern of change is still useful to assess the validity of modeling results.

Model simulation of the Feather River was made for the 25-yr flood series from 1972 to 1997. The simulated changes in channel geometry were also compared with the measured channel changes for the same time duration. Such a comparison is a part of the calibration study.

4.6.1 Spatial Variations in Sediment Delivery—Spatial variations of sediment delivery during the 25-yr time span are shown in Fig. 14. The pattern of sediment delivery has a general increasing trend toward downstream, indicating erosion from the channel reach with local variations. Such a trend indicates that more sediment will be removed from the channel boundary although sediment deposition occurs in certain short reaches, notably in gravel pits.

At the upstream end, the inflow of bed sediment to the river reach is the 3,000 cubic yards of spawning gravel introduced into the river channel in 1982. The amount of delivery in the Feather River passing the Thermalito Afterbay Outlet confluence is 200,000 tons in 25 years. This amount is much greater than the sediment introduced. The net erosion from the channel boundary of the Low Flow Reach is the difference of these two numbers, which is approximately 196,000 tons.

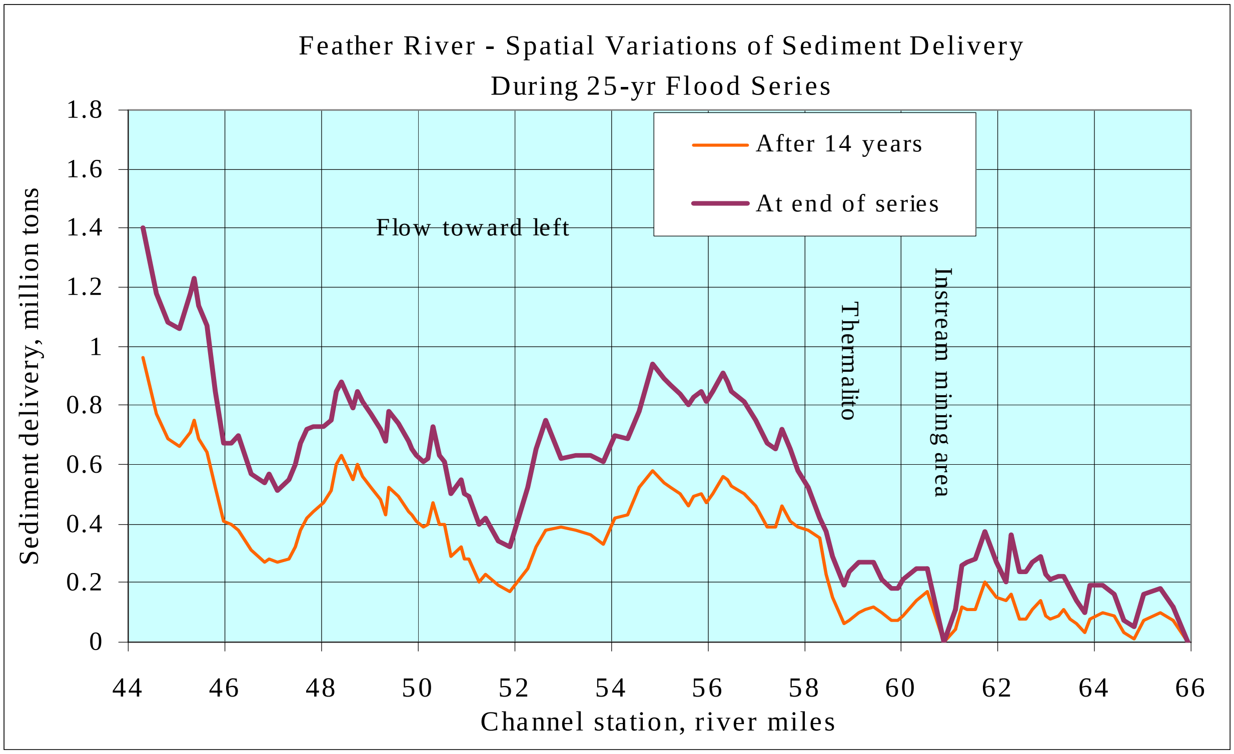

Fig. 14. Time and spatial variations of sediment delivery during the 25-yr flood series

While erosion is the general trend of change for the Low Flow Reach, there is a noted exception to this trend due to the gravel pit located near river mile 61. The small dip in sediment delivery at this location indicates sediment storage in the gravel pit.

The spatial pattern of sediment delivery shows a sharp rise in delivery in the Feather River just below the Thermalito Afterbay Outlet confluence. This trend is related to the increase in river flow from Thermalito Afterbay Outlet and therefore an increase in erosion from the channel boundary. Along the High Flow Reach, the general trend depicted by the delivery pattern is sediment erosion from the channel boundary with local exceptions. The net erosion from the channel boundary for the High Flow Reach is the increase in delivery from the upstream end of the reach to the other end. In this case, sediment inflow is the delivery passing river mile 58.8 at the upstream end; sediment outflow is the delivery passing river mile 44.3 at the downstream end. This net erosion is about 1.2 million tons in 25 years.

The two dips in sediment delivery are near river miles 47 and 52, respectively. Sediment storage is predicted at these two locations, related primarily to the channel geometry. At these locations, the channel has a large cross-sectional area of flow, a low velocity and has a low sediment transport capacity, and as a result, some of the transported sediment settles.

It was mentioned before that a comparison of channel-bed profile changes is not a good indication of channel-bed aggradation and degradation. This is because the change at a cross section due to scour or fill is by no means uniformly distributed across the bed width. In some case, the thalweg may undergo scour (degradation) but the adjacent bed areas may have fill (aggradation), and vice versa. The net change in cross-sectional area at a cross section cannot be determined based on the changes in channel-bed profile alone, but it can be determined based on the spatial variations in sediment delivery. The net scour or fill is the difference in sediment delivery from one channel station to the other. An increase in delivery toward downstream indicates scour. A decrease in delivery means sediment deposition. The amount of scour or fill can easily be converted into volume change within the reach or cross-sectional area change at a channel station.

4.6.2 Changes in Channel Geometry—Changes in channel geometry are depicted by the simulated changes in channel bed profile shown in Fig. 15 and the changes in channel cross sections included in Appendix B. The simulated changes should also be compared with the measured changes, which are provided by the difference between Blodgett cross-sectional profiles of 1972 and the Corps cross-sectional profiles of 1997. The original channel geometry is based on the 1997 Corps data, which is the most comprehensive river data available. Although the simulated results pertain to future changes, it is the working hypothesis that the trend of changes predicted for the future should also be consistent with the previous changes from 1972 to 1997,

The channel bed has become armored as a result of channel boundary scour in the last four decades. Future changes to channel geometry are limited by bed armoring. It can be seen from these results that channel changes are generally limited in magnitude. Those reaches near mining areas are subject to greater changes than other areas.

As shown in Fig. 15, channel-bed degradation is predicted at most cross sections and aggradation at fewer locations. This general degradation trend is consistent with the continued erosion along the channel reach. Changes in channel cross section include channel bed scour and fill, changes in channel width and lateral migration at channel bends. These changes are closely inter-related as the channel adjusts in response to the reduced sediment supply.

While the alluvial bed is subject to scour and fill that are induced by the imbalance in longitudinal sediment discharge, such channel bed development may also be caused by transverse sediment movement due to channel curvature. The transverse bed slope in curved channels is related to the spiral motion or secondary currents. Because of the streamwise variation in spiral motion, uneven bed topography is usually produced, characterized by a lower bed elevation near the concave bank. The intensity of spiral motion is directly related to the discharge. Therefore, the non-uniformity in bed topography is more pronounced at high flow and it becomes partially eliminated during the subsequent low flow. This explains why an observer of the post flood channel may fail to recognize the uneven bed scour under the muddy water at high flow. If the bank protection for a stream is designed based on the simulated pattern of channel bed scour, variable toe elevations for the banks should be used to provide an effective protection.

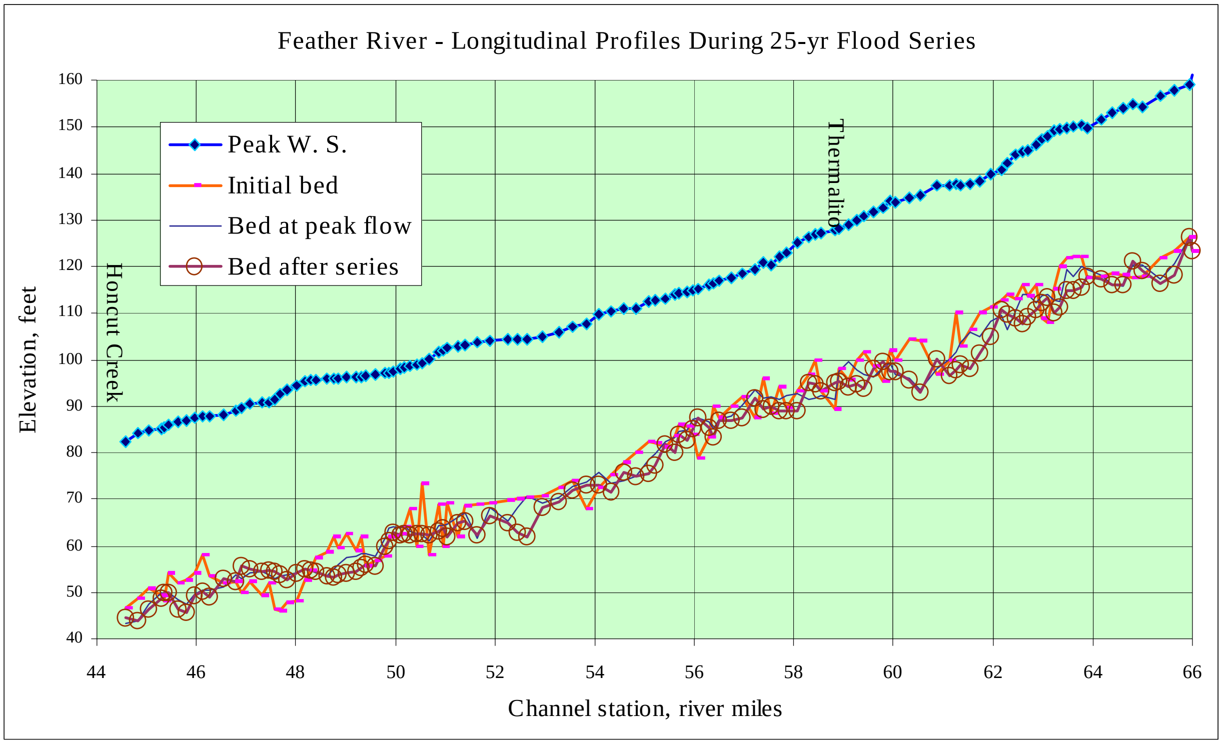

Fig. 15. Water-surface and channel-bed profile changes during the 25-yr flood series

At channel bends, the channel bed has a transverse slope, as exemplified by the cross-sectional profiles at sections 44.59, 45.29, 46.00, 46.82, 47.07, 47.32, 47.72, 48.19, 48.87, 49.40, 50.87, 50.97, and 54.59. The channel bed is lower near the concave bank and higher near the convex bank. Bank protection has already been installed along the concave banks at many channel bends. With bank protection, lateral migration of the channel is constrained by the rigid structure. There are also locations along channel bends where the concave bank is not protected, then lateral migration can be expected at these locations as illustrated by the changes at sections 45.80, 45.65, 46.28, 61.73 and 61.95.

Sediment budget through a river/reservoir system is closely related to scour and fill of the river. It should be very clear that scour or fill at a cross section is by no means uniformly distributed across the channel width. Scour of the bed may be accompanied by scour or fill of the overbank area, or vice versa. Such complex adjustments in channel morphology directly affect the hydraulics of flow and sediment transport. *It must therefore be emphasized that fluvial simulation must be based on an erodible boundary model instead of an erodible bed model*.

4.6.3 Effects of Spawning Gravel Feeding—Spawning gravel was introduced into the Lower Feather River on September 1, 1982 at river mile 65.89 just below the Fish Barrier Dam. Such spawning gravel has a median diameter of 35 mm; it is considerably smaller than the armored bed material in size. The total amount of sediment introduced was 3,000 cubic yards. In the modeling study, sediment introduction into the river channel was specified in the data file. The input data include the date of sediment introduction, the grain size distribution, and the rate of sediment introduction. It was assumed that the total amount of sediment was introduced into the river channel uniformly on September 12, 1982. For a period of 12 hours during the daytime, the uniform introduction rate was 1.062 cubic feet (net volume) per second.

The introduction of 3,000 cubic yards of spawning gravel into the channel changed the composition of the bed material. The effects of sediment introduction on grain size distribution were simulated in the model. The results are shown in Fig. 16 by the spatial and time variations of median sediment size, or d_{50}, along the river channel. The median sizes of bed sediment became generally smaller than the initial sizes four months after sediment introduction. But these sizes became coarser with time. The effects of spawning gravel feeding become insignificant one year later. Coarsening of the bed material is related to sediment sorting during the erosion processes.

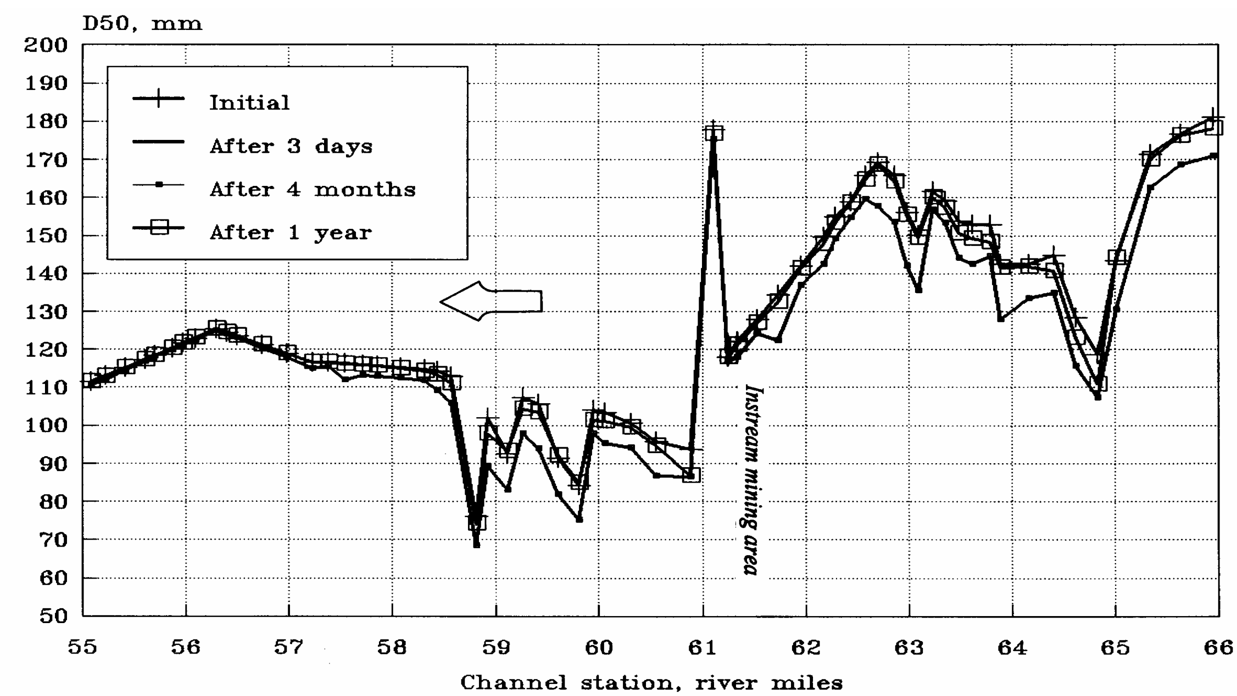

Fig. 16. Time and spatial variations of median grain size after spawning gravel feeding

The introduction of 3,000 cubic yards of spawning gravel only had limited and temporal effects on bed material composition. The effects due to sediment introduction should be directly related to the amount and size of sediment introduced; the effects are also influenced by the flow conditions. According to the simulated spatial variations in sediment delivery shown in Fig. 14, in the Feather River passing the Thermalito Afterbay Outlet confluence is 200,000 tons in 25 years. This is equivalent to 8,000 tons per year, which is much greater than the sediment introduced. The change in bed material composition is also related to the occurrence of floods. A major flood occurred in March 1983 shortly following the introduction of spawning gravel on September 1, 1982. The 1983 flood was responsible for the rapid coarsening of the bed material.

It is also important to point out that the channel bed of the Feather River is already armored and the armored bed inhibits sediment erosion. The spawning gravel introduced is smaller in size composition and it is therefore much more easily transported down the channel reach.

5.0 MODELING STUDY FOR 1997 FLOOD

The 1997 flood is the largest flood for the Feather River on record. River channel changes during this event were simulated and the results are presented in this section. Hydrographs for the flood event of 30 days are shown in Fig. 17. Peak flow of the event occurred on January 2, 1997. The hydrograph for the Low Flow Reach is based on records from the Oroville gage and that for the High Flow Reach is based on records from the Gridley gage.

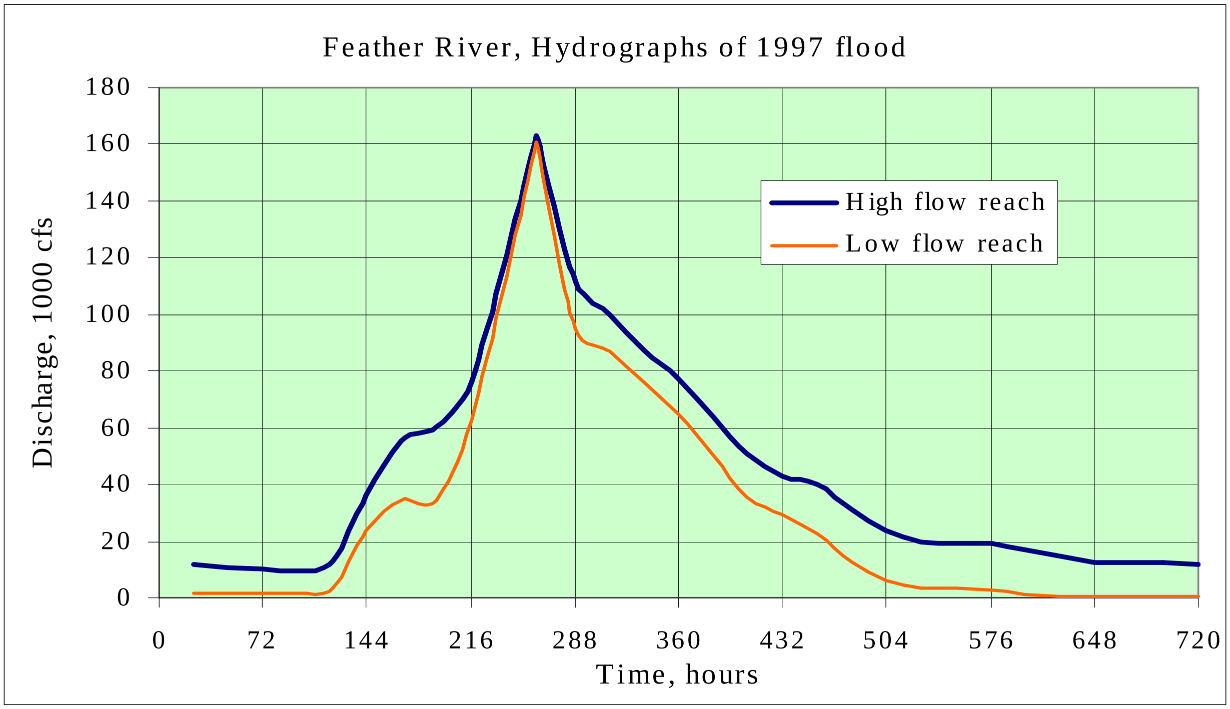

Fig. 17. Hydrographs of the 1997 flood

5.1 SEDIMENT DELIVERY FOR 1997 FLOOD

Time and spatial variations of sediment delivery along the river reach during the 1997 flood are shown in Fig. 18. The pattern of spatial variations is characterized by local changes with only a mild increasing trend toward downstream. This pattern of sediment delivery indicates that the stream channel undergoes both scour and fill changes along the study channel reach. The non-uniformity in sediment delivery indicates that the channel reach is not in sediment equilibrium.

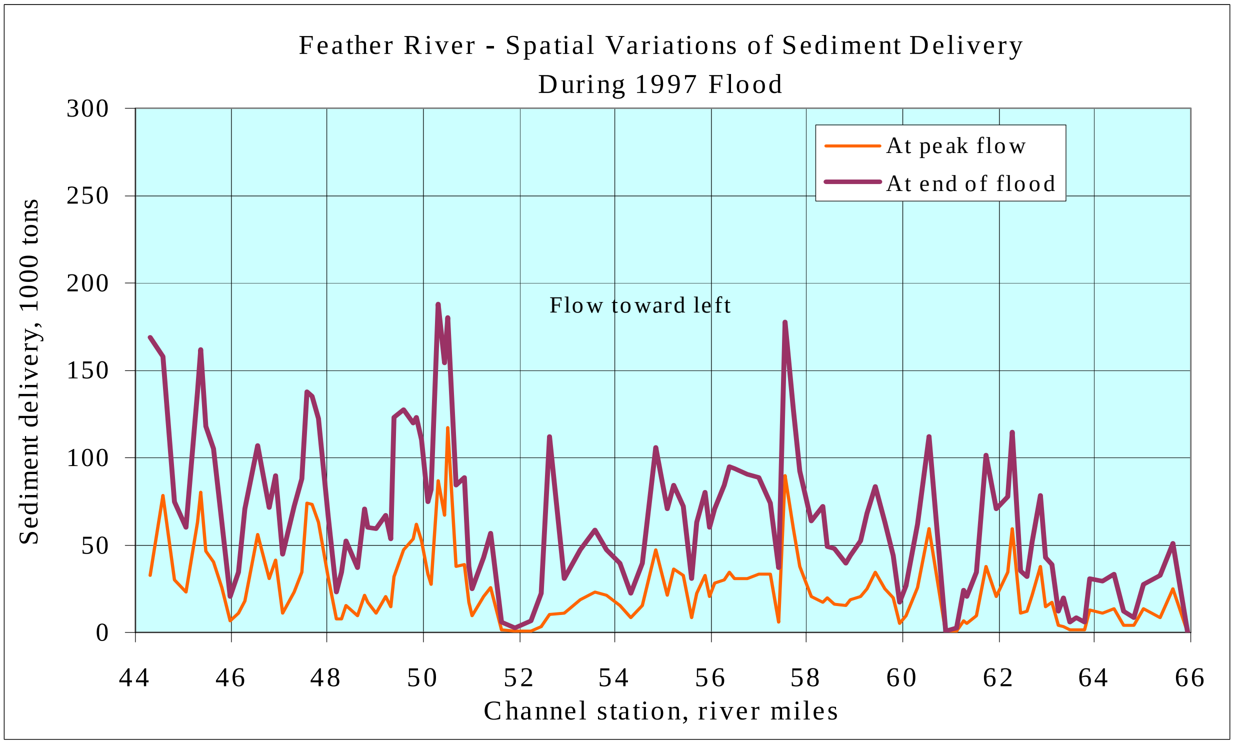

Fig. 18. Time and spatial variations of sediment delivery during the 1997 flood

The scour and fill changes are related to the non-uniformity in channel geometry as the hydraulic geometry of the gravel bed river is characterized by the riffle and pool sequence. The flow velocity and sediment transport vary from riffle to pool. During low to moderate flows, the flow velocity and sediment transport are usually higher on riffles than in pools. But at high flow, the flow velocity and sediment transport are usually greater in pools than on riffles. In other words, velocity and sediment transport reversal occurs with the flow discharge. Dynamic equilibrium is the direction toward which each river channel evolves. Uniformity in sediment transport is a condition for dynamic equilibrium. A river channel is always adjusting toward establishing uniformity in sediment transport. As the velocity and sediment transport reverse from riffle to pool with the discharge, the uniformity in sediment transport may never be attained although each river channel is constantly adjusting toward that direction. The dips in sediment delivery are at locations where less sediment transport occurred during the 1997 event and peaks are at locations with greater sediment transport.

The peak water surface profile for the 1997 flood is higher than the bankfull stage along most of the channel reach; therefore, a part of the floodwater spreads out to the broad floodplain. The overbank flow has a much lower velocity and limited sediment transport capacity. While sediment transport is directly related to the discharge, an increase in discharge above the bankfull stage does not contribute to a proportional increase in sediment transport.

The mild increasing trend in sediment transport indicates net sediment removal from the channel reach. For this flood event, the net sediment removal is the increase in delivery from the upstream end to the downstream end of the study reach and this amount is about 170,000 tons. In comparison to the sediment removal during the 25-yr flood series, this amount is relatively small. In others, sediment removal from the channel reach is attributed primarily to the long-term flood series.

5.2 WATER-SURFACE AND CHANNEL BED PROFILE CHANGES FOR 1997 FLOOD

Modeled water-surface profile and channel-bed profile changes are shown in Fig. 19. The channel bed has become armored as a result of channel boundary scour in the last four decades. Future channel changes are limited by bed armoring. It can be seen from the graphical results that channel bed changes are generally limited in magnitude. Those reaches near mining areas are subject to greater changes than other areas.

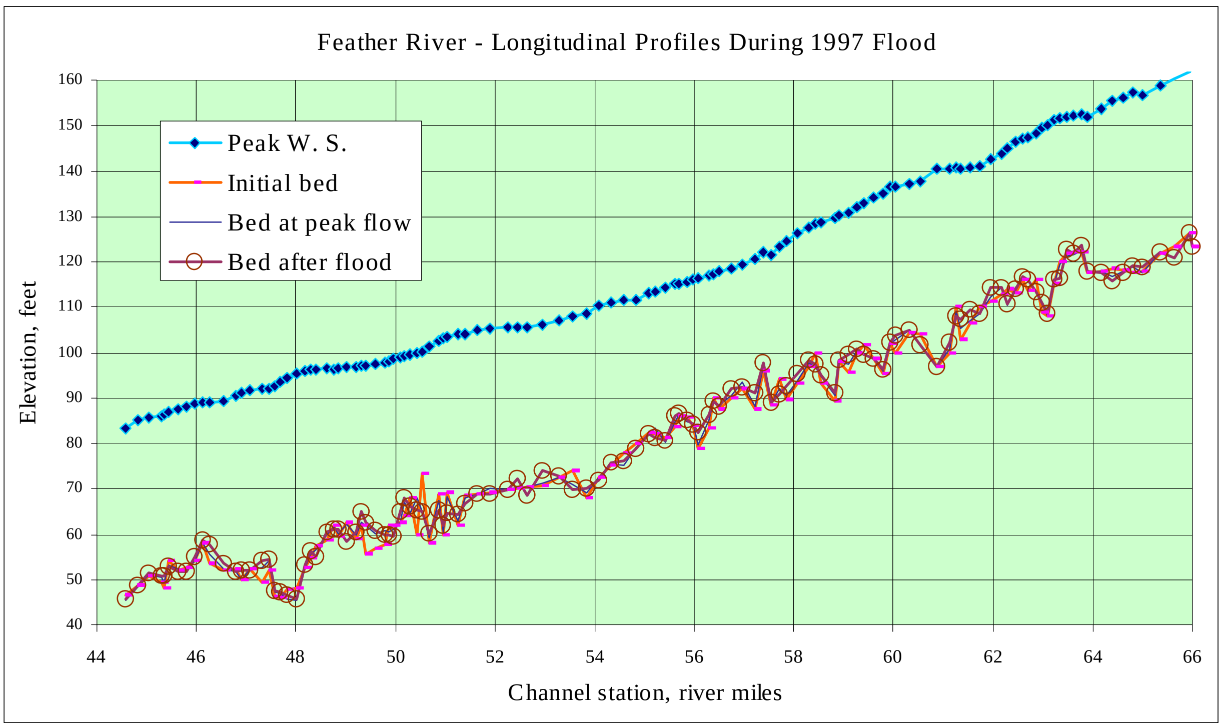

Fig. 19. Water-surface and channel bed profile changes during the 1997 flood

As shown in Fig. 19, channel-bed profile changes include both scour and fill of the channel bed. Such changes are relatively small in comparison to the long-term changes during the 25-yr flood series. The non-uniformity in channel bed profile is preserved during the major flood event.

6.0 MODELING STUDY FOR 50-YR FLOOD SERIES

A modeling study was made based on a 50-yr flood series in order to assess potential stream channel changes in the extended time period of the next 50 years. The available flow records cover the time period from 1967 to 2002, which is 35 years in total duration. In order to simulate the flow of 50 years, part of the flow records was used twice. The 50-yr flood series selected for the modeling study has the starting date of October 1, 1997, consistent with the time of the Army Corps cross-sectional data measurment. The

50-yr series used the flow records is from 1997 to the end of records in 2002, and then it uses the complete flow records from 1967 to 2002, and then it repeats the records from 1967 to 1977. The plotted peak flow that is near the mid point of the series is for the February 19, 1986 flood, which has the peak discharge of 150,000 cfs for the High Flow Reach and 134,000 for the Low Flow Reach.

The Oroville Dam has had effects on stream channel changes. The stream channel may be considered to be in an approximate state of dynamic equilibrium before the Oroville Dam. After the dam completion, the flow has eroded bed material from the channel boundary with little replenishment. In the process of erosion, finer grains are removed more easily than coarser grains. Coarsening of the bed material has thus occurred and the channel bed has gradually become armored. In order to determine the effects of bed armoring, modeling study for river channel changes were made for the two following conditions of the riverbed:

(1) Natural river bed composition before the dam, and

(2) Existing armored river bed.

Stream channel changes include changes in channel geometry as well as bed sediment composition. It is important to know if bed composition will continue to change in the future. Changes in bed sediment are also related to the changes in river channel geometry. Simulated results for the 50-yr flood series are presented as shown in Figs. 20, 21, 22, 23 and 24; they are described below.

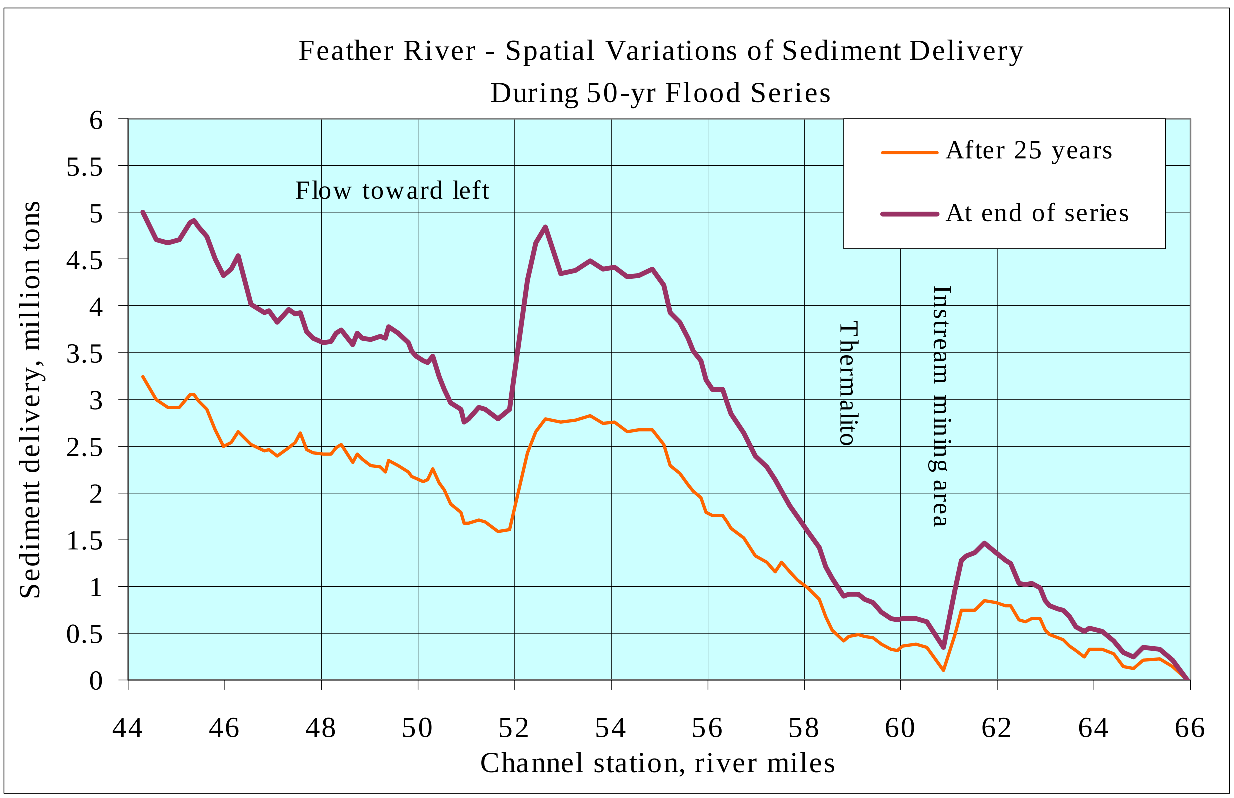

Fig. 20. Time and spatial variations of sediment delivery during the 50-yr flood series for natural bed

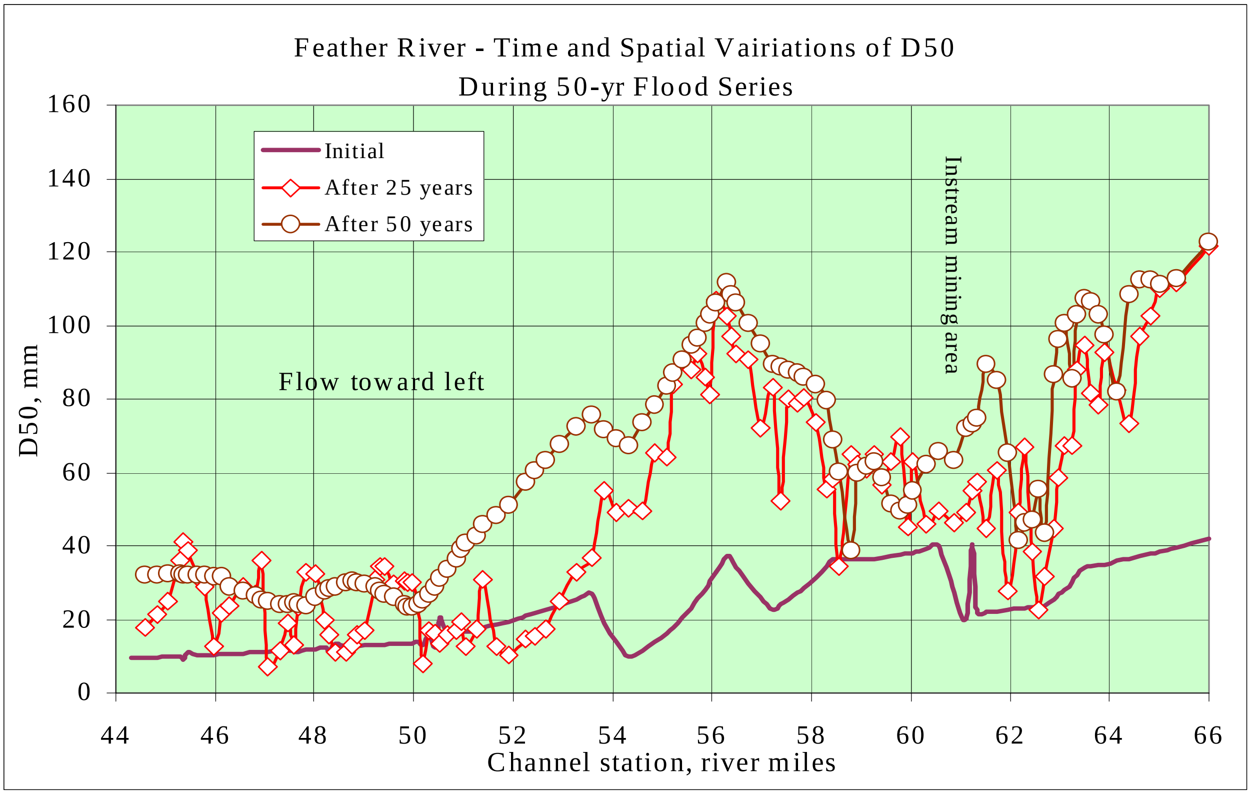

Fig. 21. Time and spatial variations of median grain size during the 50-yr flood series for natural bed

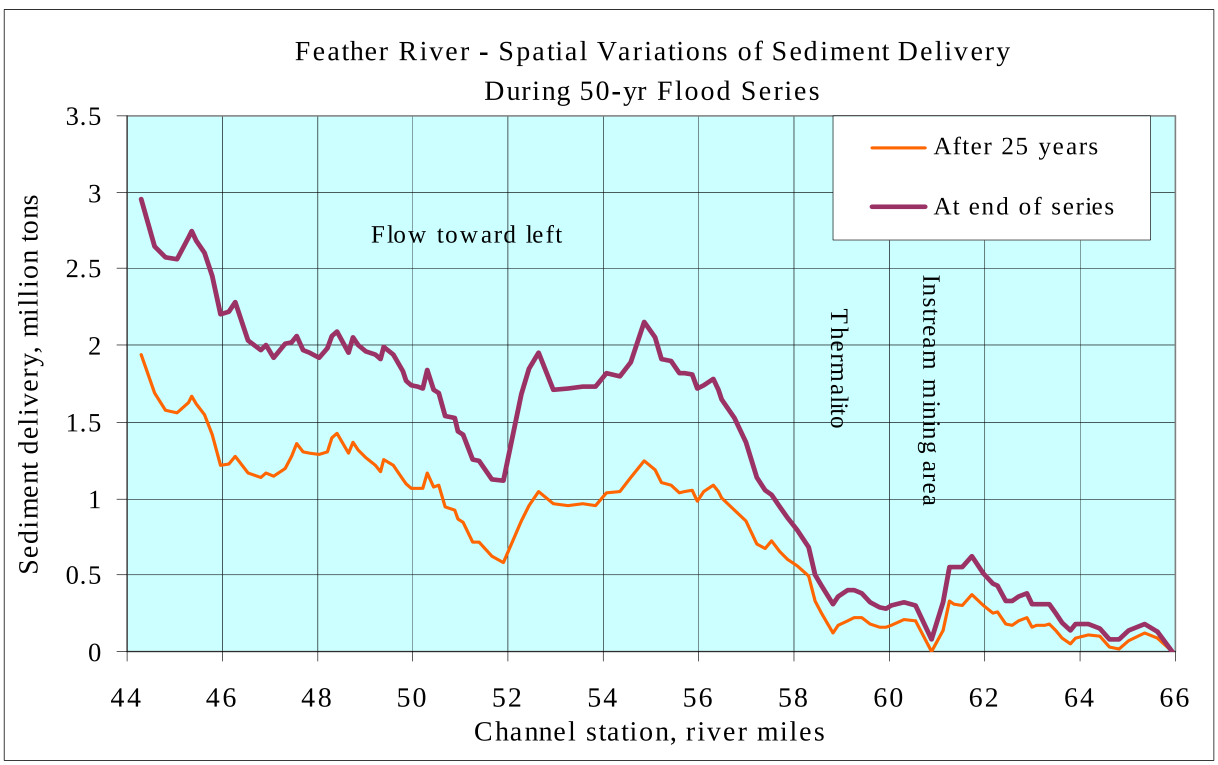

Fig. 22. Time and spatial variations of sediment delivery during the 50-yr flood series for armored bed

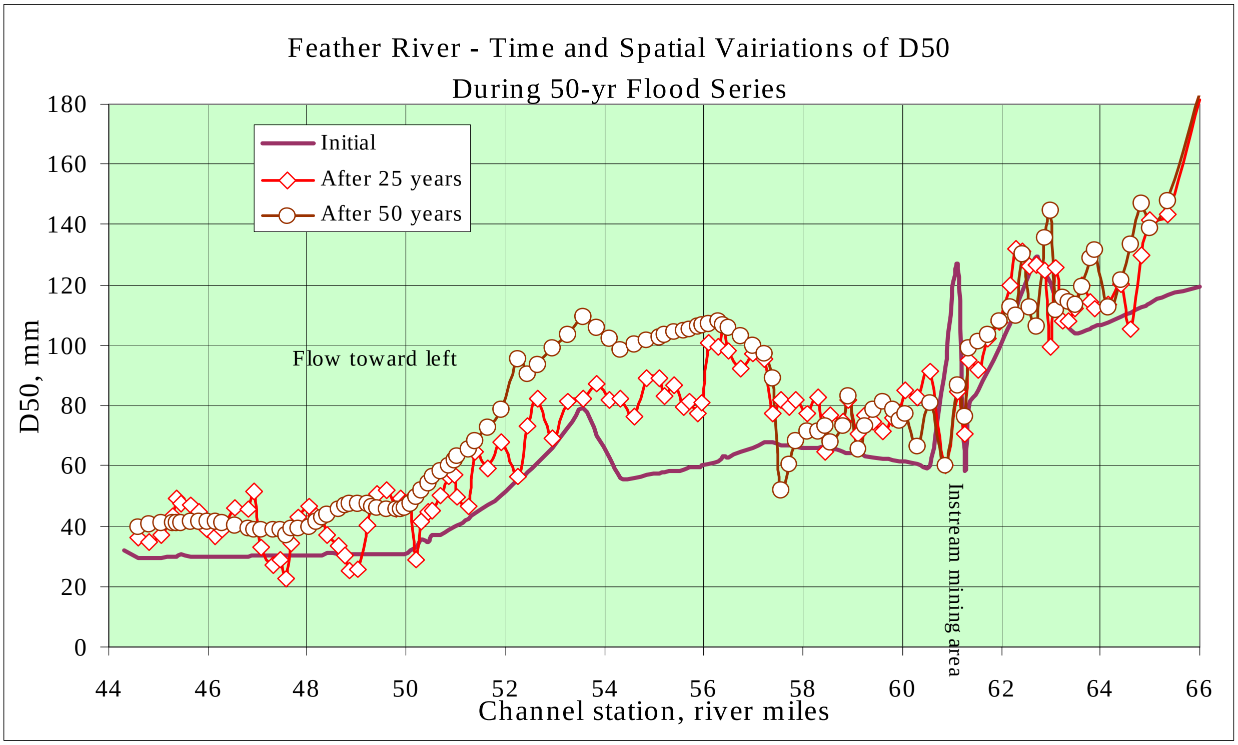

Fig. 23. Time and spatial variations of median grain size during the 50-yr flood series for armored bed

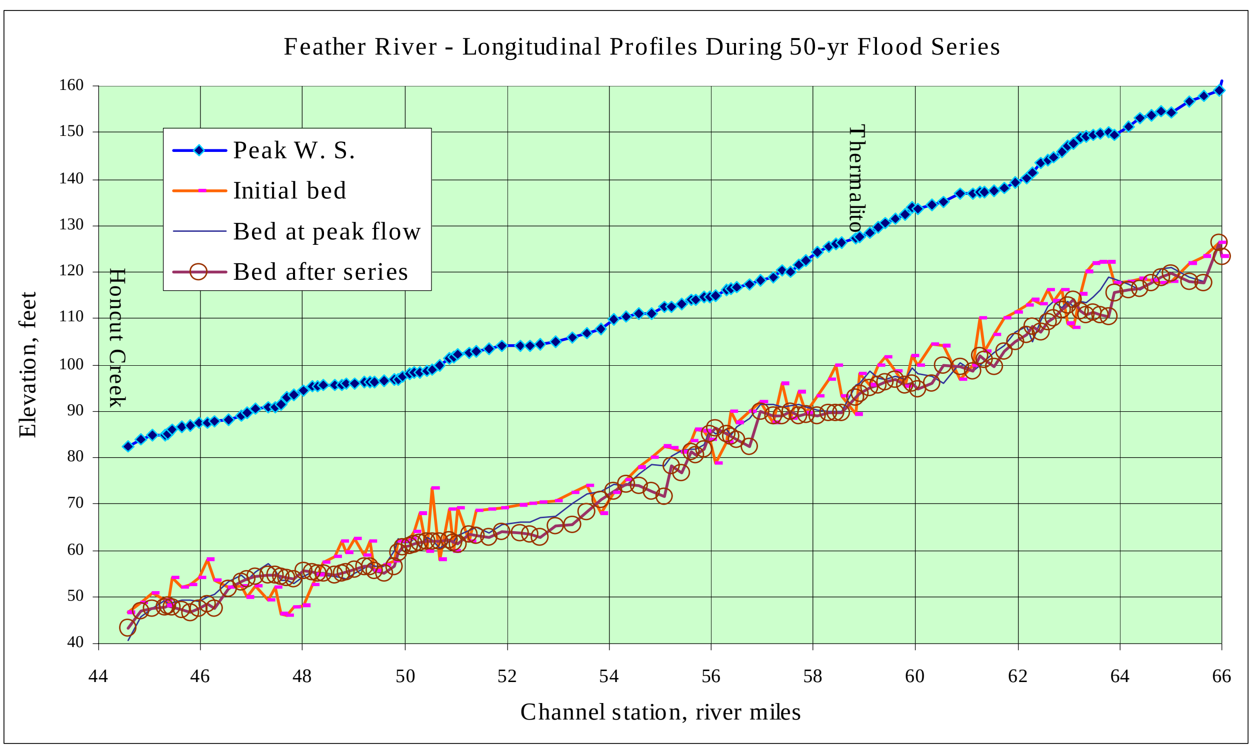

Fig. 24. Water-surface and channel bed profile changes during the 50-yr flood series for armored bed

6.1 TIME AND SPATIAL VARIATIONS IN SEDIMENT DELIVERY AND GRAIN SIZE

Time and spatial variations in sediment delivery and grain size were simulated for the natural channel bed and the armored channel bed. The results are described below separately.

6.1.1 Natural Channel Bed—The modeling study for the natural channel bed was made based on the natural grain size distributions for the bed material. Since the bed material in the subsurface layer is more or less unaffected by bed armoring; grain size distributions of subsurface bed samples are used as the initial bed material composition for the natural bed. The results of simulation using the 50-yr flood series are shown in Figs. 20 and 21.

Time and spatial variations of sediment delivery are shown in Fig. 20. The pattern of spatial variations has a generally increasing trend toward downstream, with local exceptions. The increasing trend indicates net sediment removal from the channel reach. For the 50-yr time period, the net sediment removal is the increase in delivery from the upstream end to the downstream end of the study reach and this amount is about 5.5 million tons. Fig. 20 also shows that the net sediment removal in the first 25-yr time period is about 3.2 million tons. From these numbers, it may be stated that sediment removal from the channel reach has a higher initial rate and the rate of removal slows down with time.

While there is a general trend of sediment removal from the channel reach, Fig 20 also shows a dip in sediment delivery near river mile 52. This dip indicates long-term sediment deposition in the vicinity.

Time and spatial variations of median grain size are shown in Fig. 21. The initial grain sizes are quite uniform along the channel reach with only limited spatial variations. At the end of the 50 years, the grain sizes become coarser and less uniform along the channel reach. In time variation, the grain sizes are getting coarser with time. In spatial variation, the grain sizes become less uniform along the channel reach with coarser grain sizes near the upstream end and decreasing sizes toward downstream. In other words, sediment coarsening and bed armoring develops starting from the upstream end and such effects propagate gradually toward downstream. The simulated grain sizes at the end of the 50-yr time period are similar to the grain sizes in the existing armored layer.

6.1.2. Armored Channel Bed—The existing channel bed along the study reach of the Feather River is armored. Grain size distributions of the existing surface bed layer are used for the armored channel bed. The results of simulation using the 50-yr flood series are shown in Figs. 22, 23 and 24.

Time and spatial variations of sediment delivery are shown in Fig. 22. The pattern of spatial variations has a generally increasing trend toward downstream, with local exceptions. The increasing trend indicates net sediment removal from the channel reach. For the 50-yr time period, the net sediment removal is the increase in delivery from the upstream end to the downstream end of the study reach and this amount is about 2.9 million tons. Fig. 22 also shows that the net sediment removal in the first 25-yr time period is about 1.9 million tons. From these numbers, it may be stated that sediment removal from the channel reach has a higher initial rate and the rate of removal slows down with time.

The net sediment removal of 2.9 million tons is much less that the net removal of 5.5 million tons for the natural channel bed. Such a comparison shows that sediment delivery has largely slowed down as the channel bed has become armored.

The initial grain sizes for the armored bed have a decreasing trend toward downstream. Time and spatial variations of grain sizes in the 50-yr time span are depicted in Fig. 23. In time variation, the grain sizes are getting generally coarser with time. In spatial variation, the grain sizes become less uniform along the channel reach with coarser grain sizes near the upstream end and decreasing sizes toward downstream. In other words, sediment coarsening and bed armoring continue to develop starting from the upstream end and they propagate gradually toward downstream.

The changes in grain sizes for the natural channel bed and armored channel bed are now compared. For the natural bed, the average median grain size for the study reach is about 23 mm. After 50 years, the reach-averaged median grain size becomes 60 mm. The reach-averaged median grain size for the existing armored bed is about 60 mm. The simulated median grain size after 50 years is 75 mm. This comparison shows that the coarsening slows down with time. As the bed material of the surface layer becomes coarser, the bed becomes less mobile, less sediment is removed by erosion.

The spatial pattern of sediment delivery shows a sharp rise in delivery in the Feather River just below the Thermalito Afterbay Outlet confluence. This trend is related to the increase in river flow from Thermalito Afterbay Outlet and therefore an increase in erosion from the channel boundary. Along the High Flow Reach, the general trend depicted by the delivery pattern is sediment erosion from the channel boundary with local exceptions. The net erosion from the channel boundary for the High Flow Reach is the increase in delivery from the upstream end of the reach to the downstream end. In this case, sediment inflow is the delivery passing river mile 58.8 at the upstream end; sediment outflow is the delivery passing river mile 44.3 at the downstream end. This net erosion is about 2.6 million tons in 50 years.

The two dips in sediment delivery are near river miles 52 and 54, respectively. Sediment storage is predicted at these two locations, related primarily to the channel geometry. At these locations, the channel has a lower sediment transport capacity and as a result, some of the transported sediment settles.

It was mentioned before that a comparison of channel-bed profile changes is not a good indication of channel-bed aggradation and degradation. This is because the change at a cross section due to scour or fill is by no means uniformly distributed across the bed width. In some case, the thalweg may undergo scour (degradation) but the adjacent bed areas may have fill (aggradation), and vice versa. The net change in cross-sectional area at a cross section cannot be determined based on the changes in channel-bed profile alone, but it can be determined based on the spatial variations in sediment delivery. The net scour or fill is the difference in sediment delivery from one channel station to the other. An increase in delivery toward downstream indicates scour. A decrease in delivery means sediment deposition. The amount of scour or fill can easily be converted into volume change within the reach or cross-sectional area change at a channel station.

6.1.3. Summary—From the study results, it may be stated the channel reach is subject to net erosion with local exceptions. In the process of erosion, finer sediments are more easily removed from the channel boundary and coarser sediments are usually left behind. The selective sediment transport and removal by size, or sediment sorting, has resulted in gradual coarsening of the bed material. Bed material coarsening is more pronounced near the dam and the effects decrease toward downstream.

Sediment removal from the channel reach has a higher initial rate and the rate of removal slows down with time. The armored bed inhibits erosion from the channel boundary.

6.2 WATER-SURFACE AND CHANNEL-BED PROFILE CHANGES

Simulated peak water-surface channel bed changes during the 50-yr flood series are shown in Fig. 24. The channel-bed profile pertains to the invert (or thalweg) elevations. Changes in channel-bed profile in this figure depict channel-bed aggradation and degradation (or fill and scour). Both aggradation and degradation are depicted in the figure except more sections are predicted to undergo degradation than aggradation. Since the channel-bed profile is the profile of the thalweg (minimum bed elevation), it is not a good indication of channel bed aggradation and degradation for a cross section as explained below. Changes at a cross section due to scour or fill are by no means uniformly distributed across the bed width. In some case, the thalweg may undergo scour (degradation) but the adjacent bed areas may have fill (aggradation), and vice versa. The net change in cross-sectional area at a cross section cannot be determined based on the changes in channel-bed profile alone. One must also consider the overall changes in cross-sectional profile.

6.3 CHANGES IN CROSS-SECTIONAL GEOMETRY

Modeled water-surface profile and channel-bed profile changes are shown in Fig. 24. Modeled cross-sectional changes are included in Appendix B. The channel bed has become armored as a result of channel boundary scour in the last four decades. Future channel changes are limited by bed armoring. It can be seen from the modeled results that channel changes are generally limited in magnitude. Those reaches near mining areas are subject to greater changes than other areas.

As shown in Fig. 24, channel-bed degradation is predicted at most cross sections and aggradation at fewer locations. This general degradation trend is consistent with the continued erosion along the channel reach.

While the alluvial bed is subject to scour and fill that are induced by the imbalance in longitudinal sediment discharge, such channel bed development may also be caused by transverse sediment movement due to channel curvature. The transverse bed slope in curved channels is related to the spiral motion or secondary currents. Because of the streamwise variation in spiral motion, uneven bed topography is usually produced, characterized by a lower bed elevation near the concave bank. The intensity of spiral motion is directly related to the discharge. Therefore, the non-uniformity in bed topography is more pronounced at high flow and it becomes partially eliminated during the subsequent low flow. This explains why an observer of the post flood channel may fail to recognize the uneven bed scour under the muddy water at high flow. If the bank protection for a stream is designed based on the simulated pattern of channel bed scour, variable toe elevations for the banks should be used to provide an effective protection.

At channel bends, the channel bed has a transverse slope, as exemplified by the cross-sectional profiles at sections 44.59, 45.29, 46.00, 46.82, 47.07, 47.32, 47.72, 48.19, 48.87, 49.40, 50.87, 50.97, and 54.59. The channel bed is lower near the concave bank and higher near the convex bank. Bank protection has already been installed along the concave banks at many channel bends. With bank protection, lateral migration of the channel is constrained by the rigid structure. There are also locations along channel bends where the concave bank is not protected, then lateral migration can be expected at these locations as illustrated by the changes at sections 45.80, 45.65, 46.28, 61.73 and 61.95.

7.0 MATHEMATICAL MODELING STUDY

Mathematical modeling of erodible channels has been advanced with the progress in the physics of fluvial processes and computer techniques. Since the actual size of a river is employed in mathematical modeling, there is no scale distortion as it is in physical modeling. The applicability and accuracy of a model depend on the physical foundation and numerical techniques employed. Mathematical modeling has the advantages of covering a long river reach, unsteady flow and sediment inflow. It is also more economical in time and expense. These aspects are well demonstrated in this study.

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Fig. 21. Time and spatial variations of median grain size during the 50-yr flood series for natural bed

Fig. 22. Time and spatial variations of sediment delivery during the 50-yr flood series for armored bed

Fig. 23. Time and spatial variations of median grain size during the 50-yr flood series for armored bed

Fig. 24. Water-surface and channel bed profile changes during the 50-yr flood series for armored bed

APPENDIX A. INPUT/OUTPUT DESCRIPTIONS FOR FLUVIAL-12

I. INPUT DESCRIPTION

The basic data requirements for a modeling study include (1) topographic maps of the river reach from the downstream end to the upstream end of study, (2) digitized data for cross sections in the HEC-2 format with cross-sectional locations shown on the accompanying topographic maps, (3) flow records or flood hydrographs and their variations along the study stream reach, it any, and (4) size distributions of sediment samples along the study reach. Additional data are required for special features of a study river reach.

The HEC-2 format for input data is used in all versions of the FLUVIAL model. Data records for HEC-2 pertaining to cross-sectional geometry (X1 and GR), job title (T1, T2, and T3), and end of job (EJ), are used in the FLUVIAL model. If a HEC-2 data file is available, it is not necessary to delete the unused records except that the information they contain are not used in the computation. For the purpose of water- and sediment-routing, additional data pertaining to sediment characteristics, flood hydrograph, etc., are required and supplied by other data records. Sequential arrangement of data records are given in the following.

Records	**Description of Record Type**
T1,T2,T3	Title Records
G1	General Use Record
G2	General Use Records for Hydrographs
G3	General Use Record
G4	General Use Record for Selected Cross-Sectional Output
G5	General Use Record
G6	General Use Record for Selecting Times for Summary Output
G7	General Use Record for Specifying Erosion Resistant Bed Layer
GS	General Use Records for Initial Sediment Compositions
GB	General Use Records for Time Variation of Base-Level
GQ	General Use Records for Stage-Discharge Relation of Downstream Section
GI	General Use Records for Time Variation of Sediment Inflow
X1	Cross-Sectional Record
XF	Record for Specifying Special Features of a Cross Section
GR	Record for Ground Profile of a Cross Section
SB	Record for Special Bridge Routine
BT	Record for Bridge Deck Definition
EJ	End of Job Record

Variable locations for each input record are shown by the field number. Each record has an input format of (A2, F6.0, 9F8.0). Field 0 occupying columns 1 and 2 is reserved for the required record identification characters. Field 1 occupies columns 3 to 8; Fields 2 to 10 occupy 8 columns each. The data records are tabulated and described in the following.

T1, T2, T3 Records - These three records are title records that are required for each job.

Field	Variable	Value	Description
0	IA	T1	Record identification characters
1-10	None		Numbers and alphameric characters for title

G1 Record - This record is required for each job, used to enter the general parameters listed below. This record is placed right after the T1, T2, and T3 records.

Field	Variable	Value	Description
0	IA	G1	Record identification characters
1	TYME	+	Starting time of computation on the hydrograph, in hours
2	ETIME	+	Ending time of computation on the hydrograph, in hours
3	DTMAX	+	Maximum time increment Δt allowed, in seconds
4	ISED	1	Select Graf's sediment transport equation.
		2	Select Yang's unit stream power equation. The sediment size is between 0.063 and 10 mm.
		3	Select Engelund-Hansen sediment equation.
		4	Select Parker gravel equation.
		5	Select Ackers-White sediment equation.
		6	Select Meyer-Peter Muller equation for bed load.
5	BEF	+	Bank erodibility factor for the study reach. This value is used for each section unless otherwise specified in Field 9 of the XF record. Use 1 for highly erodible banks; 0.5 for moderately erodible banks; and 0.2 for erosion-resistant banks. Any value between 0 and 1 may be used.
6	IUC	0	English units are used in input and output.
		1	Metric units are used in input and output.
7	CNN	+	Manning's *n* value for the study reach. This value is used for a section unless otherwise specified in Field 4 of the XF record. If bed roughness is computed based upon alluvial

			bedforms as specified in Field 5 of the G3 record, only an approximate *n* value needs to be entered here.
8	PTM1	+	First time point in hours on the hydrograph at which summary output and complete cross-sectional output are requested. It is usually the peak time, but it may be left blank if no output is requested.
9	PTM2	+	Second time point on the hydrograph in hours at which summary output and complete cross-sectional output are requested. It is usually the time just before the end of the simulation. This field may be left blank if no output is needed.
10	KPF	+	Frequency of printing summary output, in number of time steps. The default value is 1.

G2 Records - These records are required for each job, used to define the flow hydrograph(s) in the channel reach. The first one (or two) G2 records are used to define the spatial variation in water discharge along the reach; the succeeding ones are employed to define the time variation(s) of the discharge. Up to 10 hydrographs, with a maximum of 120 points for each, are currently dimensioned. See section II for tributaries. These records are placed after the G1 record.

Field	Variable	Value	Description
First G2			
0	IA	G2	Record identification characters
1	IHP1	+	Number of last cross section using the first (downstream most) hydrograph. The number of section is counted from downstream to upstream with the downstream section number being one. See also section II.
2	NP1	+	Number of points connected by straight segments used to define the first hydrograph.
3	IHP2	+	Number of last section using the second hydrograph if any. Otherwise leave it blank.
4	NP2	+	Number of points used to define the second hydrograph if any. Otherwise leave it blank.
5	IHP3	+	Number of last section using the third hydrograph if any.

			Otherwise leave it blank.
6	NP3	+	Number of points used to define the third hydrograph if any. Otherwise leave it blank.
7	IHP4	+	Number of last section using the fourth hydrograph if any. Otherwise leave it blank.
8	NP4	+	Number of points used to define the fourth hydrograph if any. Otherwise leave it blank.
9	IHP5	+	Number of last section using the fifth hydrograph if any. Otherwise leave it blank.
10	NP5	+	Number of points used to define the fifth hydrograph if any. Otherwise leave it blank.

Second G2: Note that this record is used only if more than 5 hydrographs are used for the job. It is necessary to place a negative sign in front of NP5 located in the 10th field of the first G2 record as a means to specify that more than 5 hydrographs are used.

0	IA	G2	Record identification characters
1	IHP6	+	Number of last cross section using the sixth hydrograph if any. Otherwise leave it blank.
2	NP6	+	Number of points connected by straight segments used to define the sixth hydrograph if any. Otherwise leave it blank.
3	IHP7	+	Number of last section using the seventh hydrograph if any. Otherwise leave it blank.
4	NP7	+	Number of points used to define the seventh hydrograph
5	IHP8	+	Number of last section using the eighth hydrograph if any. Otherwise leave it blank.
6	NP8	+	Number of points used to define the eighth hydrograph
7	IHP9	+	Number of last section using the ninth hydrograph if any. Otherwise leave it blank.
8	NP9	+	Number of points used to define the ninth hydrograph
9	IHP10	+	Number of last section using the tenth hydrograph if any. Otherwise leave it blank.

10	NP10	+	Number of points used to define the tenth hydrograph

Succeeding G2 Record(s)

1	Q11, Q21 Q31	+	Discharge coordinate of point 1 for each hydrograph, in ft^3/sec or m^3/sec
2	TM11,TM21 TM31	+	Time coordinate of point 1 for each hydrograph, in hours
3	Q12, Q22 Q32	+	Discharge coordinate of point 2 for each hydrograph, in cfs or cms
4	TM12,TM22 TM32	+	Time coordinate of point 2 for each hydrograph, in hours

Continue with additional discharge and time coordinates. Note that time coordinates must be in increasing order.

G3 Record - This record is used to define required and optional river channel features for a job as listed below. This record is placed after the G2 records.

Field	**Variable**	**Value**	**Description**
0	IA	G3	Record identification characters
1	S11	+	Slope of the downstream section, required for a job
2	BSP	0	One-on-one slope for rigid bank or bank protection
		+	Slope of bank protection in BSP horizontal units on 1 vertical unit. In the case of vertical bank, use 0.05 for BSP. This value is used for all cross sections unless otherwise specified in Field 8 of the XF record for a section.
3	DSOP	0	Downstream slope is allowed to vary during simulation.
		1	Downstream slope is fixed at S11 given in Field 1.
4	TEMP	0	Water temperature is 15^{o}C.
		+	Water temperature in degrees Celsius
5	ICNN	0	Manning's n defined in Field 7 of the G1 record or those in Field 4 of the XF records are used.
		1	Brownlie's formula for alluvial bed roughness is used to Calculate Manning's n in the simulation.

6	TDZAMA	0	Thickness of erodible bed layer is 100 ft (30.5 m).
		+	Thickness of erodible bed layer in ft or m. This value is applied to the entire channel reach but it may be redefined for a section using Field 10 of the XF record.
7	SPGV	0	Specific gravity of sediment is 2.65.
		+	Specific gravity of sediment
8	KGS	0	The number of size fractions for bed material is 5.
		+	The number of size fractions for bed material. It maximum value is 8.
9	PHI	0	The angle of repose for bed material is 36^{o}.
		+	Angle of repose for bed material

G4 Record - This is an optional record used to select cross sections (up to 4) to be included at each summary output. Each cross section is identified by its number which is counted from the downstream section. This record also contains other options; it is placed after the G3 record.

Field	Variable	Value	Description
0	IA	G4	Record identification characters
1	IPLT1	+	Number of cross section
2	IPLT2	+	Number of cross section
3	IPLT3	+	Number of cross section
4	IPLT4	+	Number of cross section
5	IEXCAV	+	A positive integer indicates number of cross section where sand/gravel excavation occurs.
6	GIFAC	+	A non-zero constant is used to modify sediment inflow at the upstream section.
7	PZMIN	0	Minimum bed profile during simulation run is not requested.
		1	Output file entitled TZMIN for minimum bed profile is requested.
10	REXCAV	+	A non-zero value specifies rate of sand/gravel excavation at Section IEXCAV.

G5 Record - This is an optional record used to specify miscellaneous options, including unsteady-flow routing for the job based upon the dynamic wave, bend flow characteristics. If the unsteady flow option is not used, the water-surface profile for each time step is computed using the standard-step method. When the unsteady flow option is used, the downstream water-surface elevation must be specified using the GB records.

Field	Variable	Value	Description
0	IA	G5	Record identification characters
1	DT	0	The first time step is 100 seconds.
		+	Size of the first time step in seconds.
2	IROUT	0	Unsteady water routing is not used; water-surface profiles are computed using standard-step method.
		1	Unsteady water-routing based upon the dynamic wave is used to compute stages and water discharges at all cross sections for each time step.
3	PQSS	0	No output of gradation of sediment load
		1	Gradation of sediment load is included in output in 1,000 ppm by weight.
5	TSED	0	Rate of tributary sediment inflow is 1 times the discharge ratio.
		+	Rate of tributary sediment inflow is TSED times the discharge ratio.
6	PTV	0	No output of transverse distribution of depth-averaged Velocity
		1	Transverse distribution of depth-averaged velocity is printed. The velocity distribution is for bends with fully developed transverse flow.
10	DYMAX	0	No GR points are inserted for cross sections.
		+	Maximum value of spacing between adjacent points at a cross section (ft or m). If this value is exceeded, intermediate points will be inserted by interpolation. The number of points inserted is given in Field 10 of the X3 record in output.

G6 Record - This is an optional record used to select time points for summary output. Up to 30 time points may be specified. The printing frequency (KPF) in Field 10 of the

G1 Record may be suppressed by using a large number such as 9999.

Field	Variable	Value	Description
First G6 Record			
0	IA	G6	Record identification characters
1	NKPS	+	Number of time points
Succeeding G6 Record(s)			
0	IA	G6	Record identification characters
1	SPTM(1)	+	First time point, in hours
2	SPTM(2)	+	Second time point, in hours

Continue with additional time points.

G7 Record - This is an optional record used to specify erosion resistant bed layer, such as a caliche layer, that has a lower rate of erosion.

Field	Variable	Value	Description
First G7 Record			
0	IA	G7	Record identification characters
1	KG7	+	Number of time points used to define the known erosion rate in relation to flow velocity
2	THICK	+	Thickness of erosion resistant layer, in feet
Succeeding G7 Record(s)			
0	IA	G7	Record identification characters
1	ERATE(1)	+	Erosion rate, in feet per hour
2	G7V(2)	+	Velocity, in feet per second

Continue with additional time points.

GS Record - At least two GS records are required for each job, used to specify initial bed-material compositions in the channel at the downstream and upstream cross sections. The first GS record is for the downstream section; it should be placed before the first X1 record and after the G4 record, if any. The second GS record is for the upstream section; it should be placed after all cross-sectional data and just before the EJ record. Additional GS records may be inserted between two cross sections within the stream reach, with the total number of GS records not to exceed 15. Each GS record specifies the sediment composition at the cross section located before the record. From upstream to downstream, exponential decay in sediment size is assumed for the initial distribution. Sediment composition at each section is represented by five size fractions.

Field	Variable	Value	Description
0	IA	GS	Record identification characters
1	DFF	+	Geometric mean diameter of the smallest size fraction in mm
2	PC	+	Fraction of bed material in this size range

Continue with other DFF's and PC's.

GB Records - These optional records are used to define time variation of stage (water-surface elevation) at a cross section. The first set of GB records is placed before all cross section records (X1); it specifies the downstream stage. When the GB option is used, it supersedes other methods for determining the downstream stage. Other sets of GB records may be placed in other parts of the data set; each specifies the time variation of stage for the cross section immediately following the GB records.

Field	Variable	Value	Description
First GB Record			
0	IA	GB	Record identification characters
1	KBL	+	Number of points used to define base-level changes
Succeeding GB Record(s)			
0	IA	GB	Record identification characters
1	BSLL(1)	+	Base level of point 1, in ft or m
2	TMBL(1)	+	Time coordinate of point 1, in hours
3	BSLL(2)	+	Base level of point 2, in ft or m
4	TMBL(2)	+	Time coordinate of point 2, in hours

Continue with additional elevations and time coordinates, in the increasing order of time.

GQ Records - These optional records are used to define stage-discharge relation at the downstream section. The GQ input data may not used together with the GB records.

Field	Variable	Value	Description
First GQ Record			
0	IA	GQ	Record identification characters
1	KQL	+	Number of points used to define base-level changes
Succeeding GQ Record(s)			
0	IA	GQ	Record identification characters
1	BSLL(1)	+	Base level of point 1, in ft or m
2	TMQ(1)	+	Discharge of point 1, in cfs or cms
3	BSLL(2)	+	Base level of point 2, in ft or m
4	TMQ(2)	+	Discharge of point 2, in cfs or cms

Continue with additional elevations and discharges, in the increasing order of discharge.

GI Records - These optional records are used to define time variation of sediment discharge entering the study reach through the upstream cross section. The GI input data, if included, will supersede other methods for determining sediment inflow. The sediment inflow is classified into the two following cases: (1) specified inflow at the upstream section, such as by a rating curve; and (2) sediment feeding, such as from a dam breach or a sediment feeder. These two cases are distinguished by DXU in Field 2 of this record. For the first case, sediment discharge at the upstream section is computed using size fractions of bed-material at the section, but for the second case, the size fractions of feeding material need to be specified using the PCU values in this record. The upstream section does not change in geometry for the first case but it may undergo scour or fill for the second case.

Field	Variable	Value	Description
First GI Record			
0	IA	GI	Record identification characters
1	KGI	+	Number of points used to define time variation of sediment inflow.

2	DXU	+ or 0	Channel distance measured from the upstream section to the sediment source. A zero value signifies case 1; and non-zero DXU and KGI signify case 2, for which PCU values are required.
3-10	PCU	+	Size fractions of inflow material. The number of size fractions is given in Field 8 of the G3 record and the sizes for the fractions are given in the second GS record.

Succeeding GI Record(s)

0	IA	GI	Record identification characters
1	QSU(1)	+	Sediment discharge of point 1, in cubic ft or m (net volume) per second
2	TMGI(1)	+	Time coordinate of point 1, in hours
3	QSO(2)	+	Sediment discharge of point 2
4	TMGI(2)	+	Time coordinate of point 2.

Continue with additional sediment discharges and time coordinates, in the increasing order of time coordinates.

X1 Record - This record is required for each cross section (175 cross sections can be used for the study reach); it is used to specify the cross-sectional geometry and program options applicable to that cross-section. Cross sections are arranged in sequential order starting from downstream.

Field	Variable	Value	Description
0	IA	X1	Record identification characters
1	SECNO	+	Original section number from the map
2	NP	+	Total number of stations or points on the next GR records for current cross section
7	DX	+	Length of reach between current cross section and the next downstream section along the thalweg, in feet or meters
8	YFAC	0	Cross-section stations are not modified by the factor YFAC.
		+	Factor by which all cross-section stations are multiplied to increase or decrease area. It also multiplies YC1, YC2 and CPC in the XF record, and applies to the CI record.

9	PXSECE	0	Vertical or Z coordinate of GR points are not modified.
		±	Constant by which all cross-section elevations are raised or lowered
10	NODA	0	Cross section is subject to change.
		1	Cross section is not subject to change.

XF Record - This is an optional record used to specify special features of a cross section.

Field	Variable	Value	Description
0	IA	XF	Record identification characters
1	YC1	0	Regular erodible left bank
		+	Station of rigid left bank in ft or m, to the left of which channel is nonerodible. Note: This station is located at toe of rigid bank; its value must be non-zero and must be equal to one of the Y coordinates in GR records but not the first Y coordinate.
2	YC2	0	Regular erodible right bank
	+		Station of rigid right bank, to the right of which channel is non-erodible. Note: This station is located at toe of rigid bank; its value must be equal to one of the Y coordinates in GR records but not the last Y coordinate.
3	RAD	0	Straight channel with zero curvature
		+	Radius of curvature at channel centerline in ft or m. Center of radius is on same side of channel where the station (Y-coordinate) starts.
		-	Radius of curvature at channel centerline in ft or m. Center Of radius is on opposite side of zero station. Note: RAD is used only if concave bank is rigid and so specified using the XF record. RAD produces a transverse bed scour due to curvature.
4	CN	0	Roughness of this section is the same as that given in Field 7 of the G1 record.
		+	Manning's *n* value for this section
5	CPC	0	Center of thalweg coincides with channel invert at this section.
		+	Station (Y-coordinate) of the thalweg in ft or m

6	IRC	0	Regular erodible cross section
		1	Rigid or nonerodible cross section such as drop structure or Road crossing. There is no limit on the total number of such cross sections.
8	BSP	0	Slope of bank protection is the same as that given in Field 2 of the G3 record.
		+	Slope of bank protection at this section in BSP horizontal units on 1 vertical unit. Use 0.05 for vertical bank.
		5	Slope of rigid bank is defined by the GR coordinates.
9	BEFX	0	Bank erodibility factor is defined in Field 5 of the G1 record.
		+	A value between 0.1 and 1.0 for BEFX specifies the bank erodibility factor at this section.
	RWD	+	RWD is the width of bank protection of a small channel in the floodplain. Areas outside this zone remains erodible. RWD is specified by a value greater than 1 (ft or m) in this field. When RWD is used, BEFX is not specified.
10	TDZAM	0	Erodible bed layer at this section is defined by TDZAMA in Field 6 of the G3 record.
		+	Thickness of erodible bed layer in ft or m. Only one decimal place is allowed for this number.
	ENEB	$\pm$	Elevation of non-erodible bed, used to define the crest elevation of a grade-control structure which may be above
or			
			below the existing channel bed. In order to distinguish it from TDZAM, ENEB must have the value of 1 at the second decimal place. For example, the ENEB value of 365 should be inputted as 365.01 and the ENEB value of -5.2 should be inputted as -5.21. When ENEB is specified,it supersedes TDZAM and TDZAMA

CI Record - This is an optional record used to specify channel improvement options due to excavation or fill. The excavation option modifies the cross-sectional geometry by trapezoidal excavation. Those points lower than the excavation level are not filled. The fill option modifies the cross-sectional geometry by raising the bed elevations to a prescribed level. Those points higher than the fill level are not lowered. Excavation and fill can not be used at the same time. This record should be placed after the X1 and XF records but before the GR records. The variable ADDVOL in Field 10 of this record is used to keep track of the total volume of excavation or fill along a channel reach. ADDVOL specifies the initial volume of fill or excavation. A value greater or less than 0.1 needs to be entered in this field to keep track of the total volume of fill or excavation until another ADDVOL is defined.

Field	Variable	Value	Description
0	IA	G5	Record identification characters
1	CLSTA	+	Station of the centerline of the trapezoidal excavation, expressed according to the stations in the GR records, in feet or meter.
2	CELCH	+	Elevation of channel invert for trapezoidal channel, in feet or meters.
4	XLSS	+	Side slope of trapezoidal excavation, in XLSS horizontal units for1 vertical unit.
5	ELFIL	+	Fill elevation on channel bed, in feet or meters.
6	BW	+	Bed width of trapezoidal channel, in feet or meters. This width is measured along the cross section line; therefore, a larger value should be used if a section is skewed.
10	ADDVOL	0	Volume of excavation or fill, if any, is added to the total volume already defined.
		+	Initial volume of fill on channel bed, in cubic feet or cubic meters.
		-	Initial volume of excavation from channel bed, in cubic feet Or meters.

GR Record - This record specifies the elevation and station of each point for a digitized cross section; it is required for each X1 record.

Field	Variable	Value	Description
0	IA	GR	Record identification characters
1	Z1	"	Elevation of point 1, in ft or m. It may be positive or negative.
2	Y1	"	Station of point 1, in ft or m
3	Z2	"	Elevation of point 2, in ft or m
4	Y2	"	Station of point 2, in ft or m

Continue with additional GR records using up to 79 points to describe the cross section. Stations should be in increasing order.

SB Record - This special bridge record is used to specify data in the special bridge routine. This record is used together with the BT and GR records for bridge hydraulics. This record is placed between cross sections that are upstream and downstream of the bridge.

Field	Variable	Value	Description
0	IA	SB	Record identification characters
1	XK	+	Pier shape coefficient for pier loss
2	XKOR	+	Total loss coefficient for orifice flow through bridge opening
3	COFQ	+	Discharge coefficient for weir flow overtopping bridge roadway
4	IB	+	Bridge index, starting with 1 from downstream toward upstream
5	BWC	+	Bottom width of bridge opening including any obstruction
6	BWP	0	No obstruction (pier) in the bridge
		i	Total width of obstruction (piers)
7	BAREA	+	Net area of bridge opening below the low chord in square feet
9	ELLC	+	Elevation of horizontal low chord for the bridge
10	ELTRD	+	Elevation of horizontal top-of-roadway for the bridge

BT Record - This record is used to compute conveyance in the bridge section. The BT data defines the top-of -roadway and the low chord profiles of bridge. The program uses the BT, SB and GR data to distinguish and to compute low flow, orifice flow and weir flow.

Field	Variable	Value	Description
0	IA	BT	Record identification characters
1	NRD	+	Number of points defining the bridge roadway and bridge low chord to be read on the BT records
2	RDST(1)	+	Roadway station corresponding to RDEL(1) and XLCEL(1)

3	RDEL(1)	+	Top of roadway elevation at station RDST(1)
4	XLCEL(1)	+	Low chord elevation at station RDST(1)
5	RDST(2)	+	Roadway station corresponding to RDEL(2) and XLCEL(2)
6	RDEL(2)	+	Top of roadway elevation at station RDST(2)

7	XLCEL(2)	+	Low chord elevation at station RDST(2)

Continue with additional sets of RDST, RDEL, and XLCEL.

EJ Record - This record is required following the last cross section for each job. Each group of records beginning with the T1 record is considered as a job.

Field	Variable	Value	Description
0	IA	EJ	Record identification characters
1-10			Not used

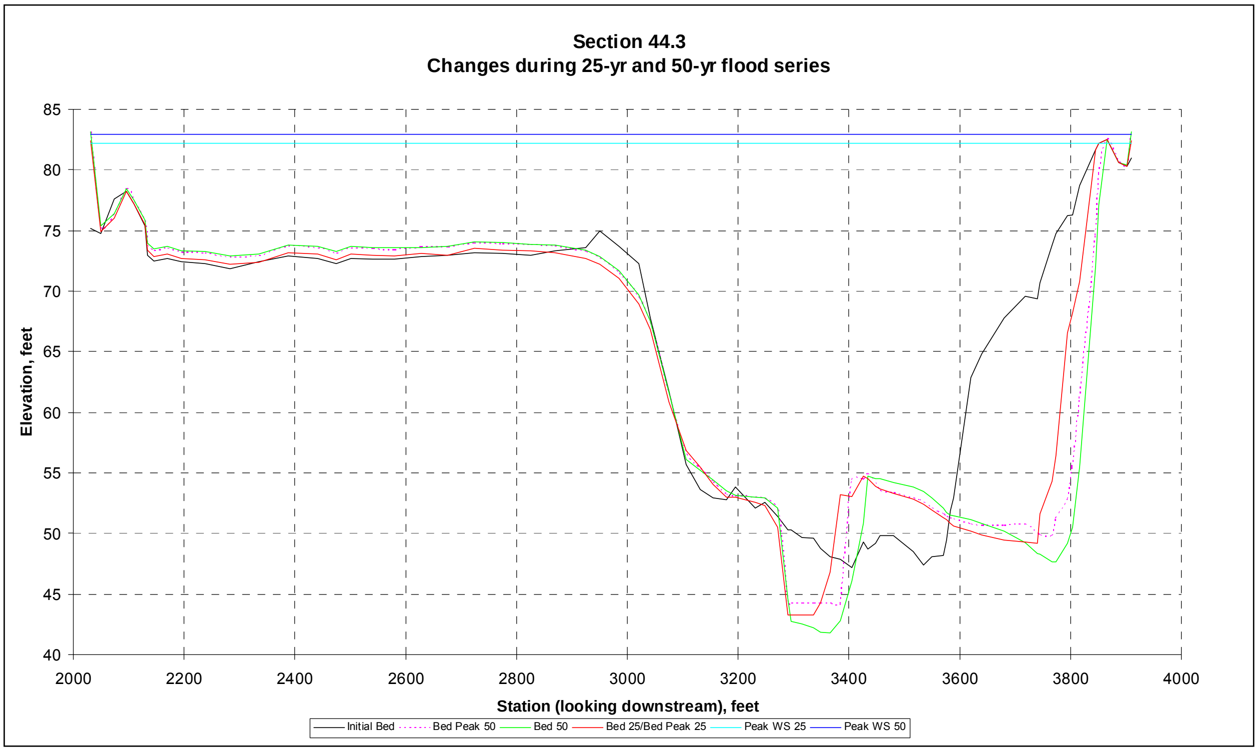
II. OUTPUT DESCRIPTION

Output of the model include initial bed-material compositions, time and spatial variations of the water-surface profile, channel width, flow depth, water discharge, velocity, energy gradient, median sediment size, and bed-material discharge. In addition, cross-sectional profiles are printed at different time intervals.

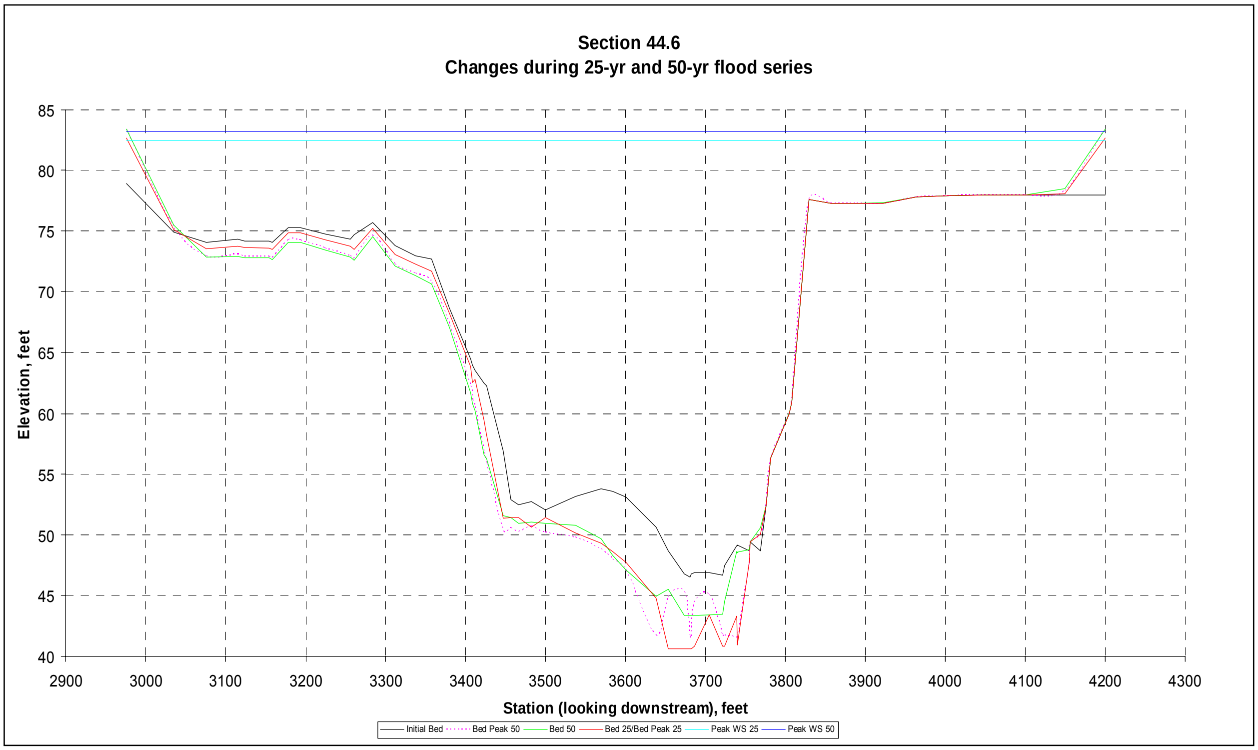
Symbols used in the output are generally descriptive, some of them are defined below:

SECTION	Cross section
TIME	Time on the hydrograph
DT	Size of the time step or Δt in sec
W.S.ELEV	Water-surface elevation in ft or m
WIDTH	Surface width of channel flow in ft or m
DEPTH	Depth of flow measured from channel invert to water surface in ft or m
Q	Discharge of flow in cfs or cms
V	Mean velocity of a cross-section in fps or mps
SLOPE	Energy gradient
D50	Median size or d_{50} of sediment load in mm
QS	Bed-material discharge for all size fractions in cfs or cms
FR	Froude number at a cross section
N	Manning's roughness coefficient
SED.YIELD	Bulk volume or weight of sediment having passed a cross section since beginning of simulation, in cubic yards or tons.
WSEL	Water-surface elevation, in ft or m
Z	Vertical coordinate (elevation) of a point on channel boundary at a cross-section, in ft or m
Y	Horizontal coordinate (station) of a point on channel boundary at a cross-section, in ft or m
DZ	Change in elevation during the current time step, in ft or m
TDZ	Total or accumulated change in elevation, in ft or m

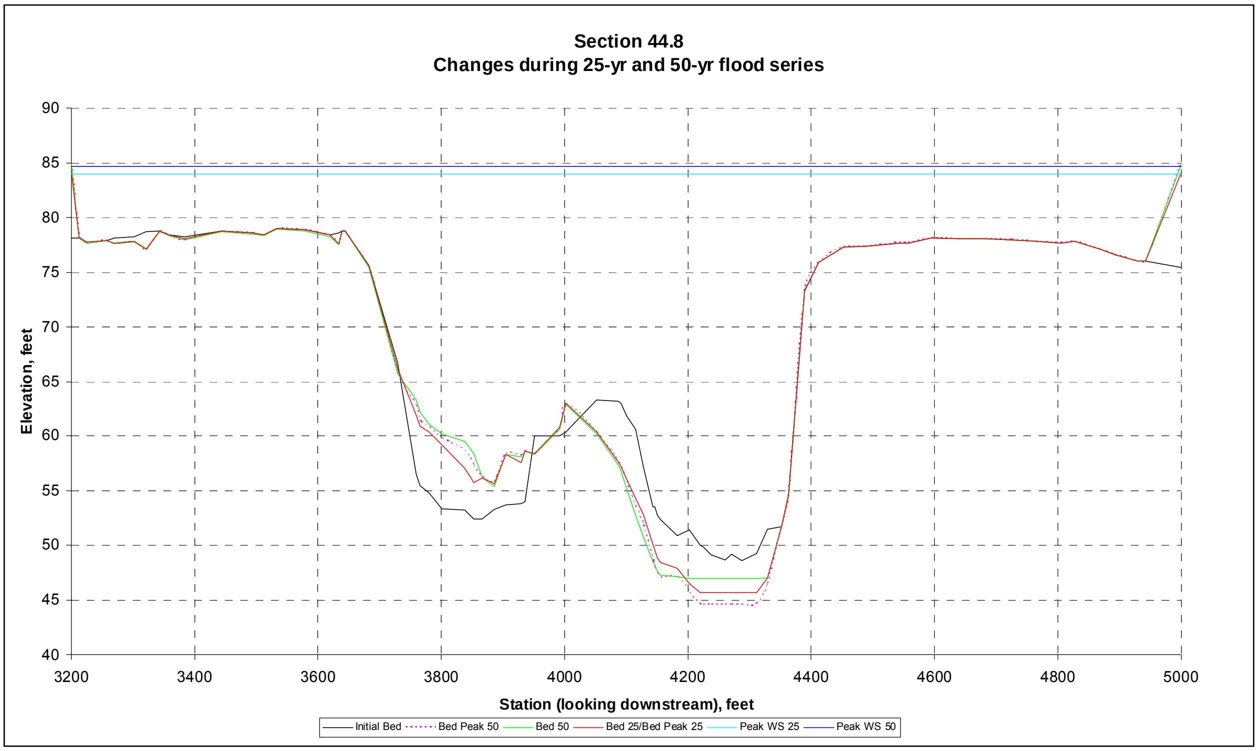
MODELED CHANNEL CHANGES FOR THE 25- AND 50- YEAR FLOOD SERIES



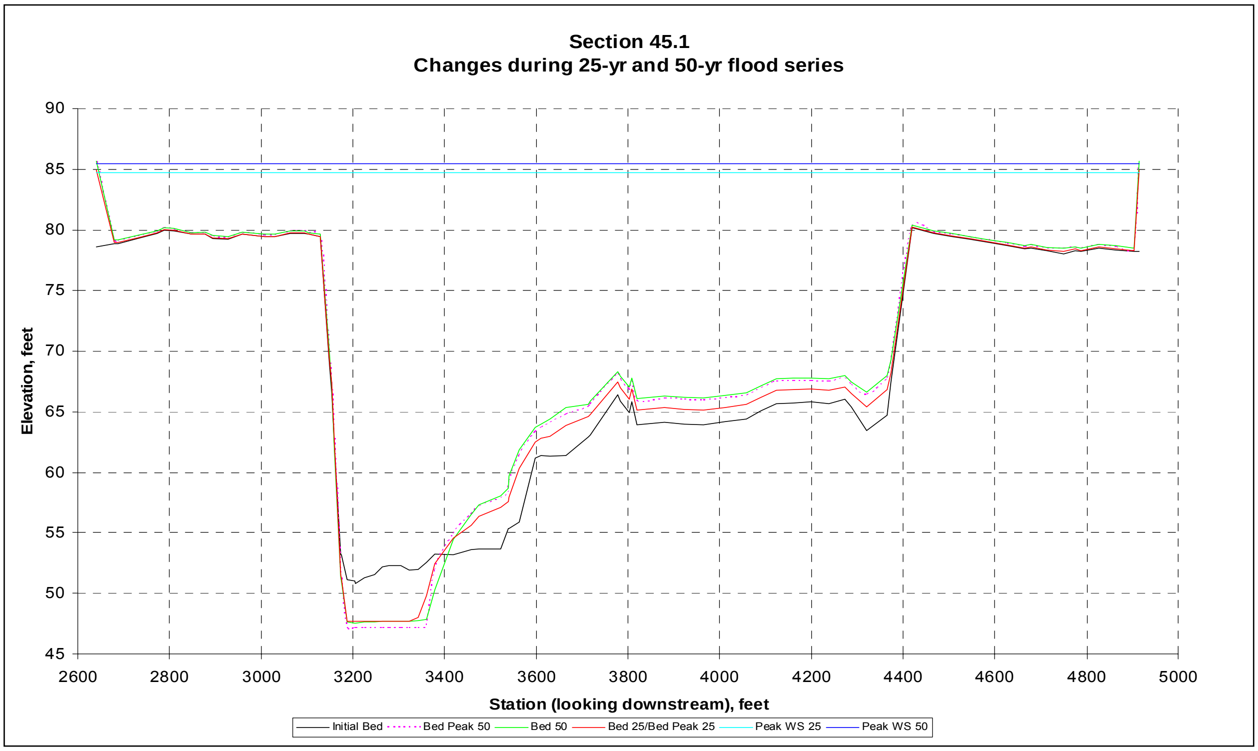
Section 44.3
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
85
80
75
70
65
60
55
50
45
40
2000
2200
2400
2600
2800
3000
3200
3400
3600
3800
4000
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50



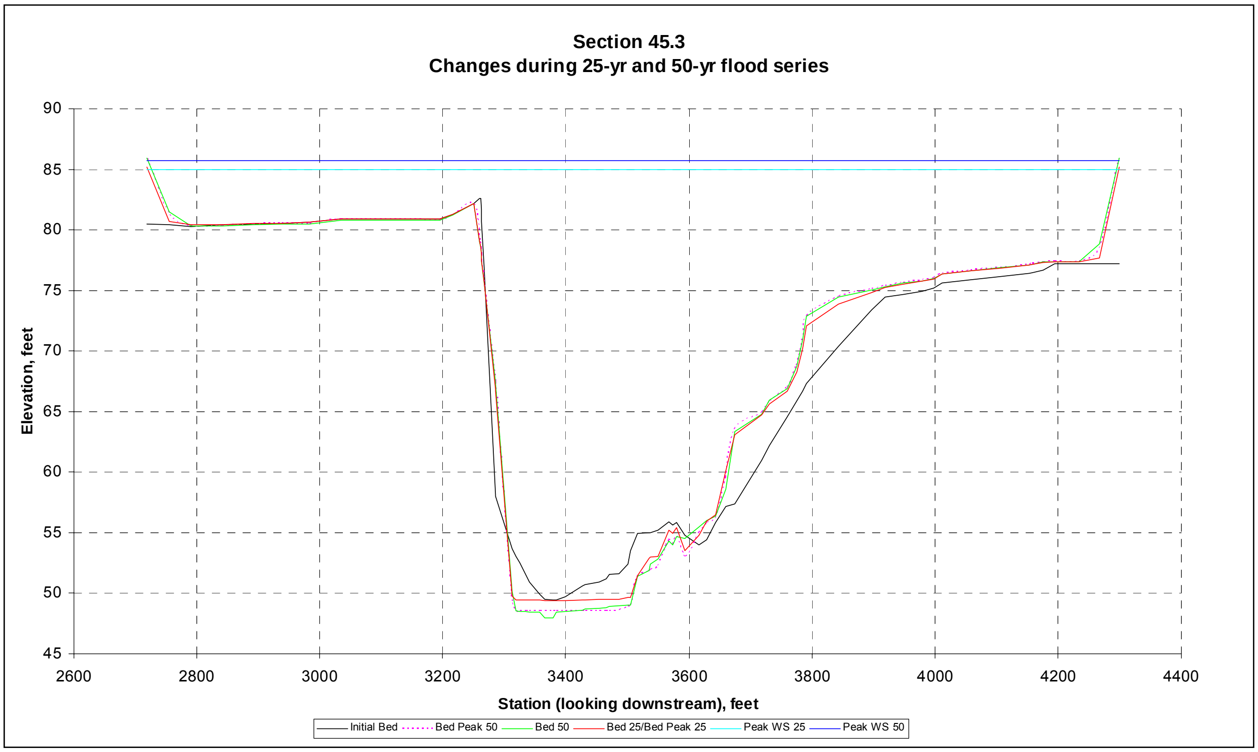
Section 44.6
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
85
80
75
70
65
60
55
50
45
40
2900
3000
3100
3200
3300
3400
3500
3600
3700
3800
3900
4000
4100
4200
4300
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

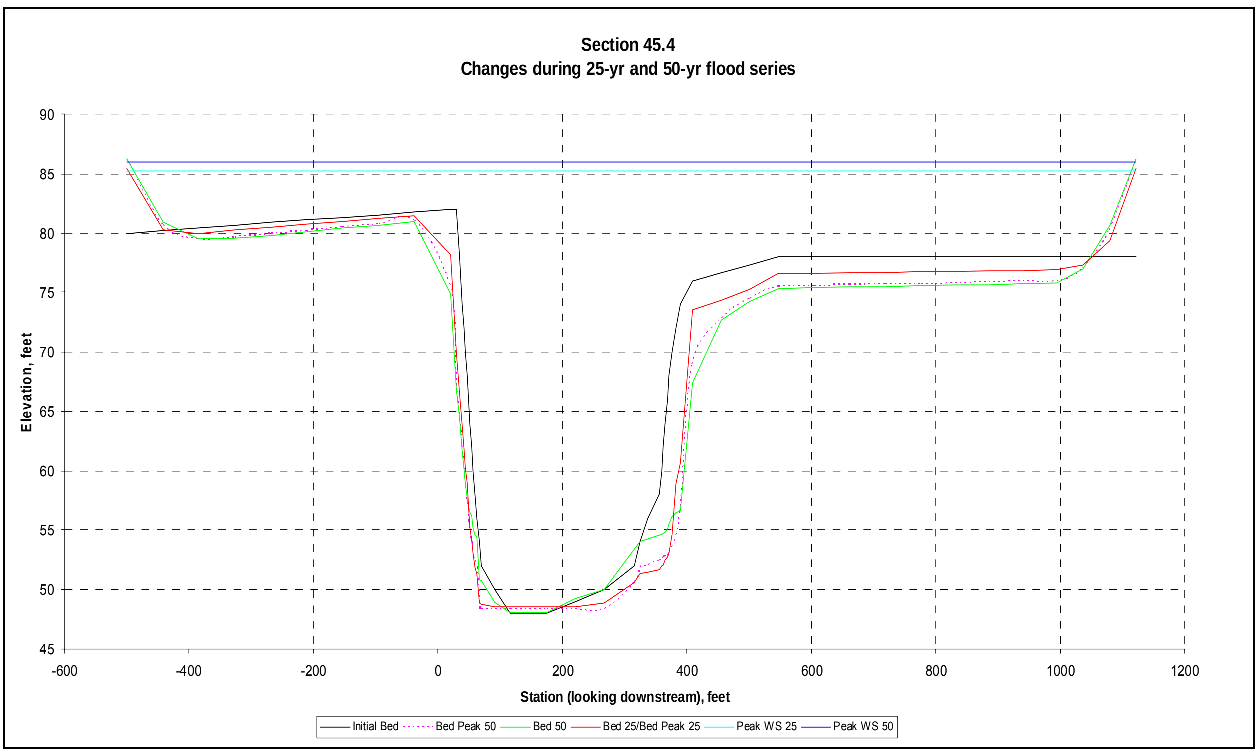


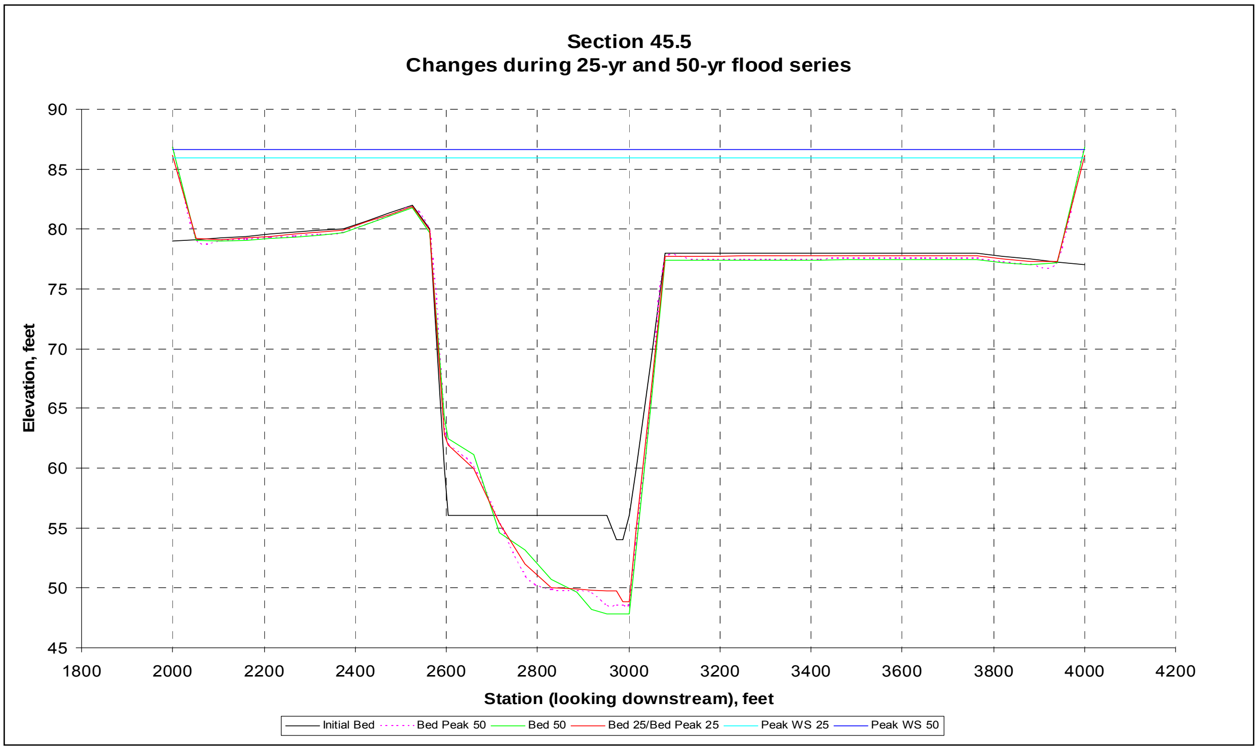
Section 44.8
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50



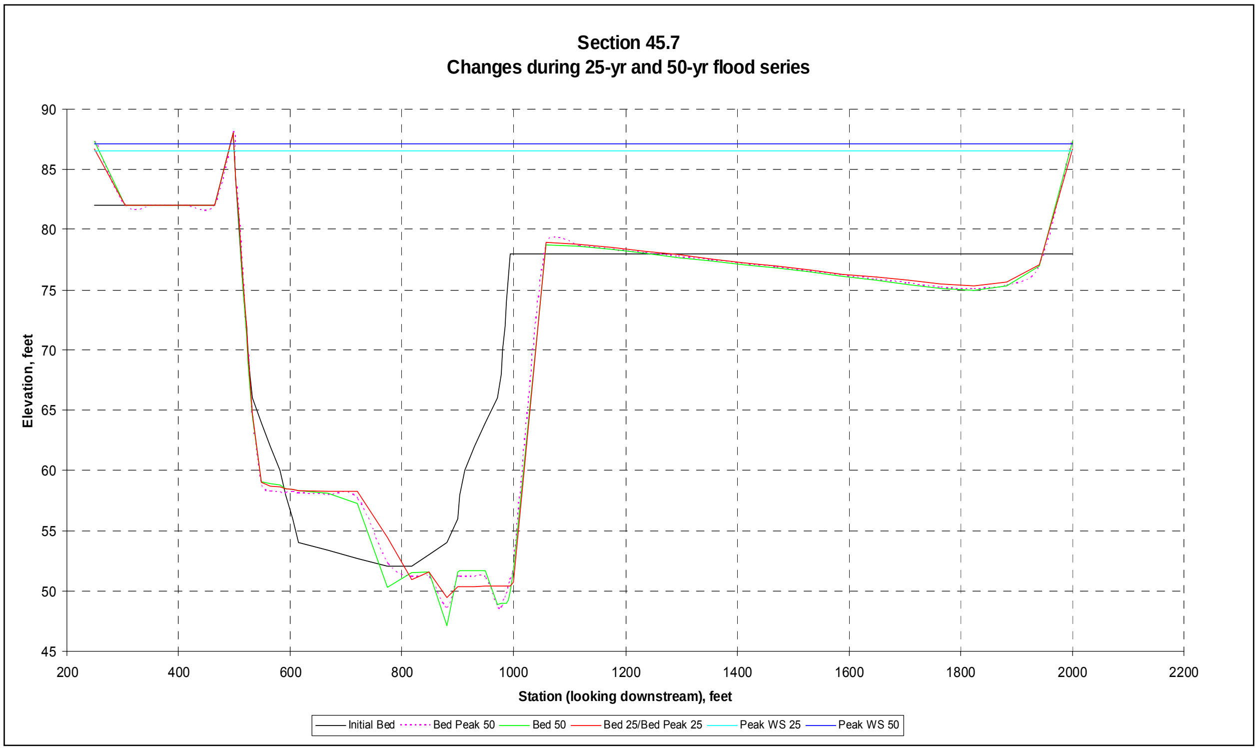
Section 45.1
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50


Section 45.3
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
90
85
80
75
70
65
60
55
50
45
2600
2800
3000
3200
3400
3600
3800
4000
4200
4400
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

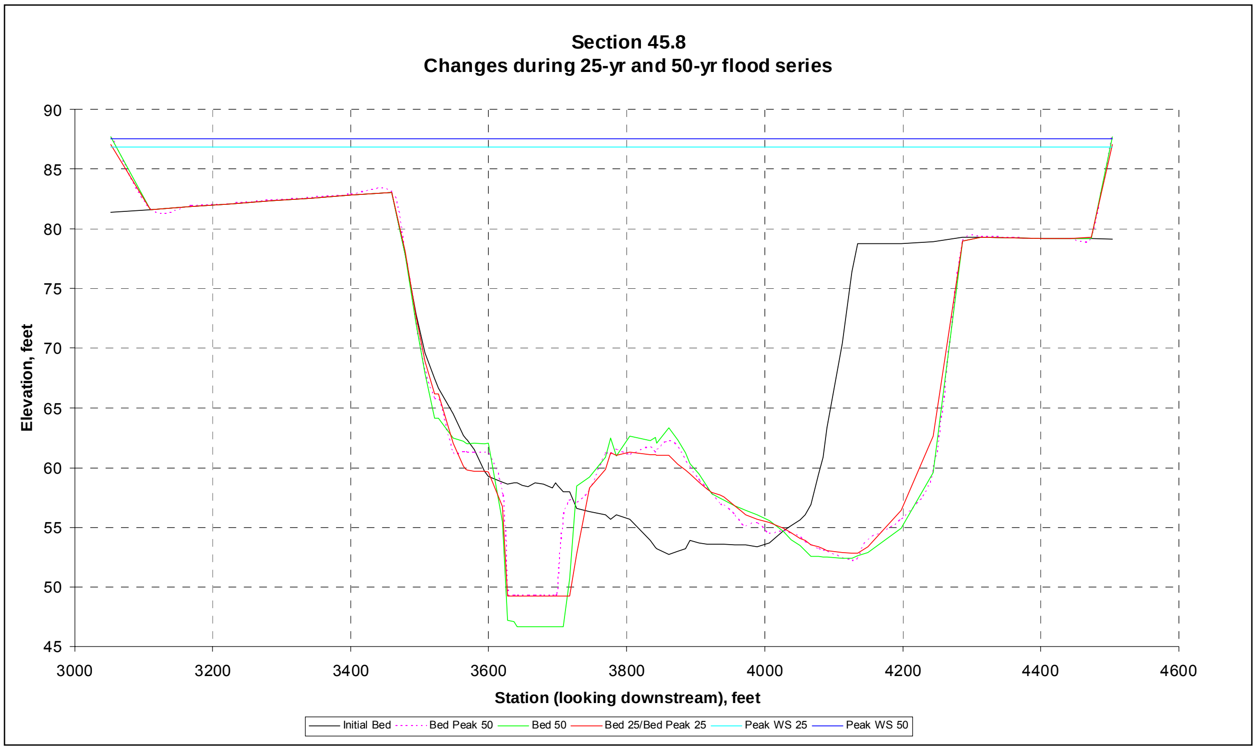

Section 45.4
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
90
85
80
75
70
65
60
55
50
45
-600
-400
-200
0
200
400
600
800
1000
1200
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

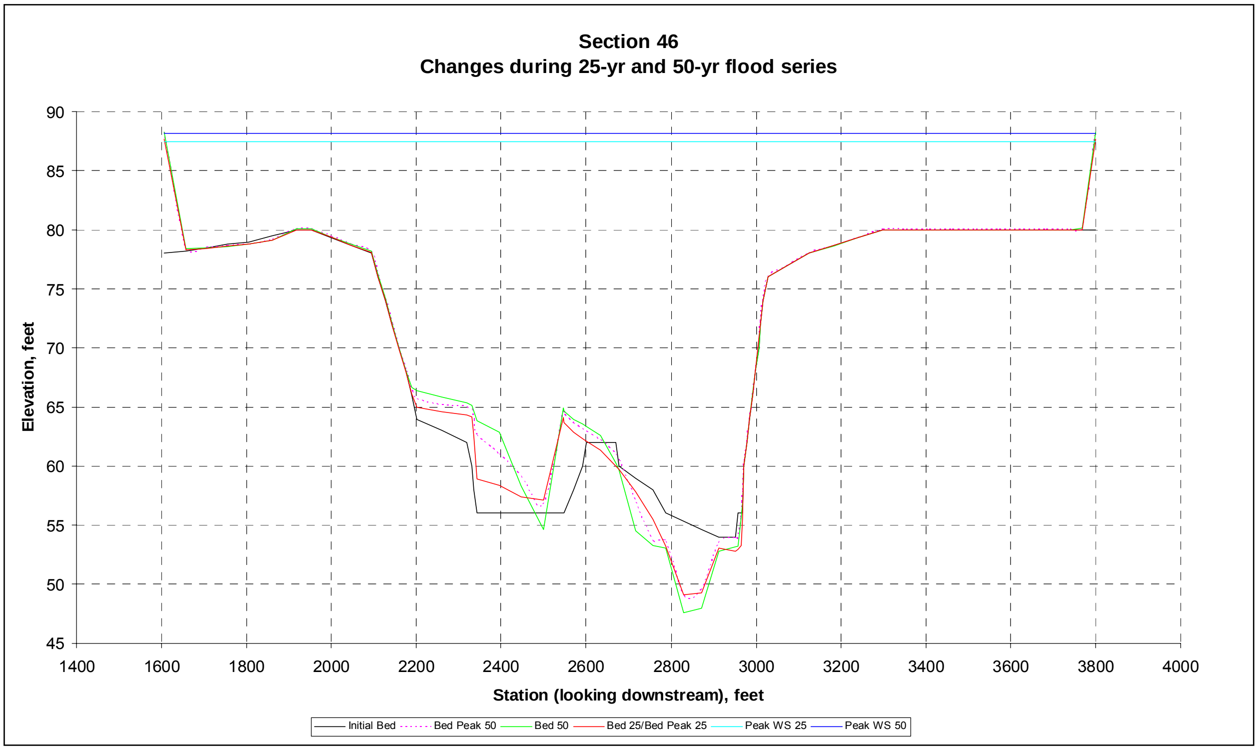


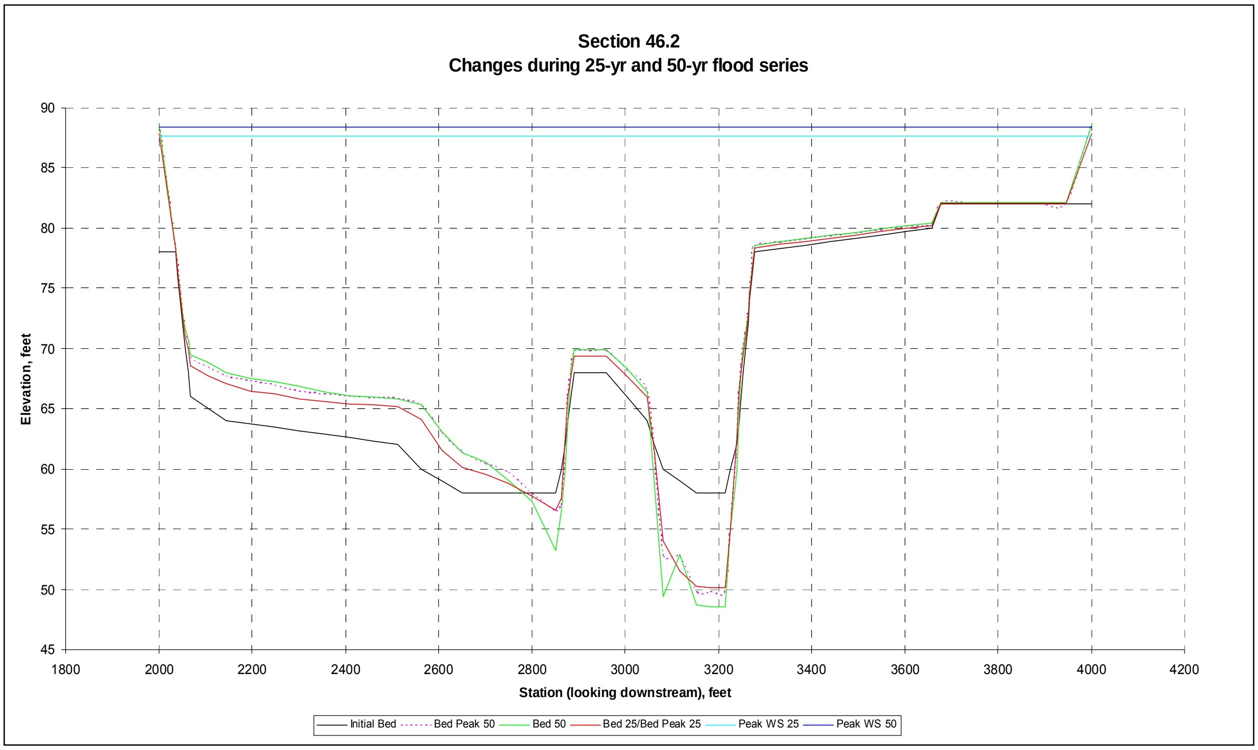
Section 45.5
Changes during 25-yr and 50-yr flood series
Elevation, feet
90
85
80
75
70
65
60
55
50
45
1800
2000
2200
2400
2600
2800
3000
3200
3400
3600
3800
4000
4200
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

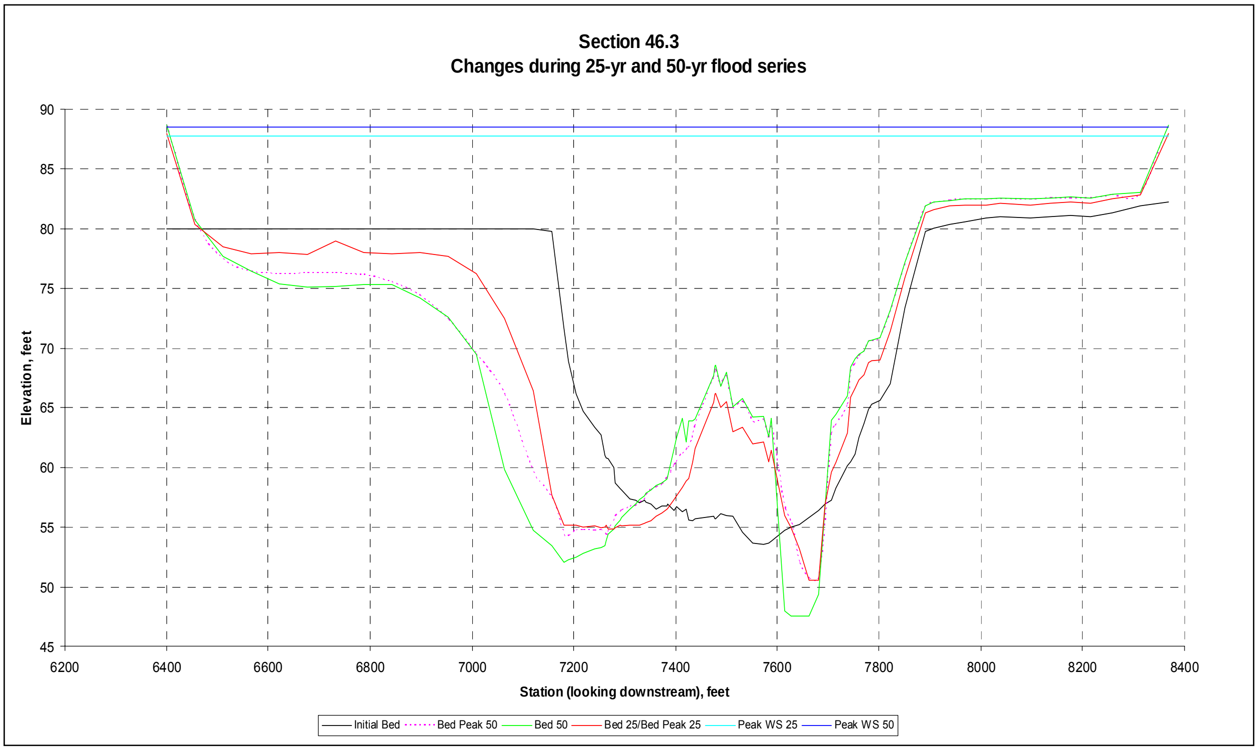


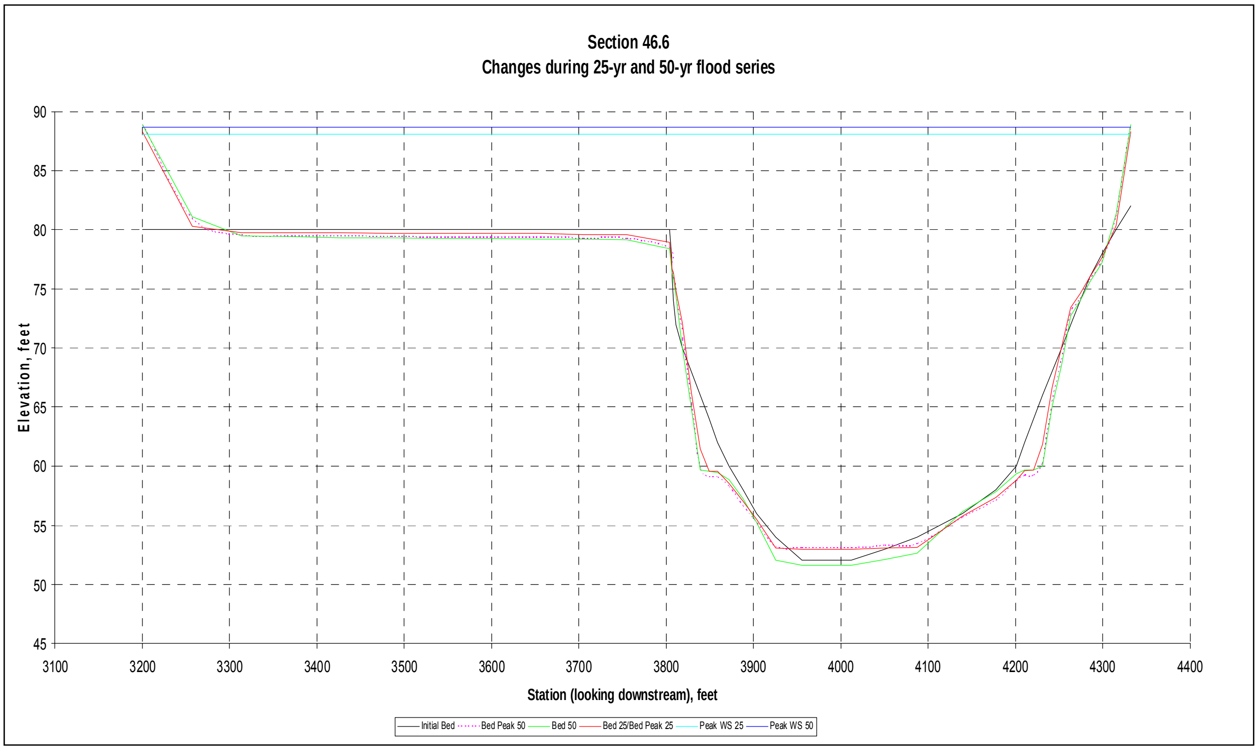
Section 45.7
Changes during 25-yr and 50-yr flood series
Elevation, feet
90
85
80
75
70
65
60
55
50
45
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

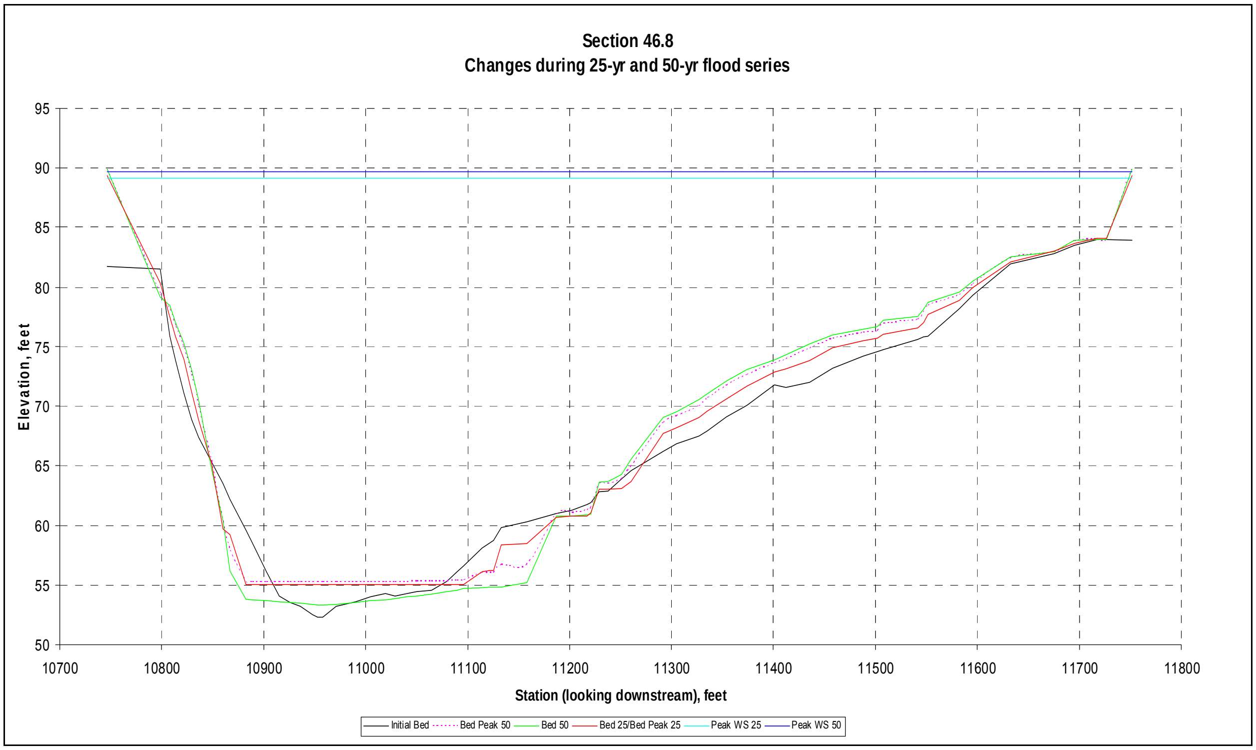

Section 45.8
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

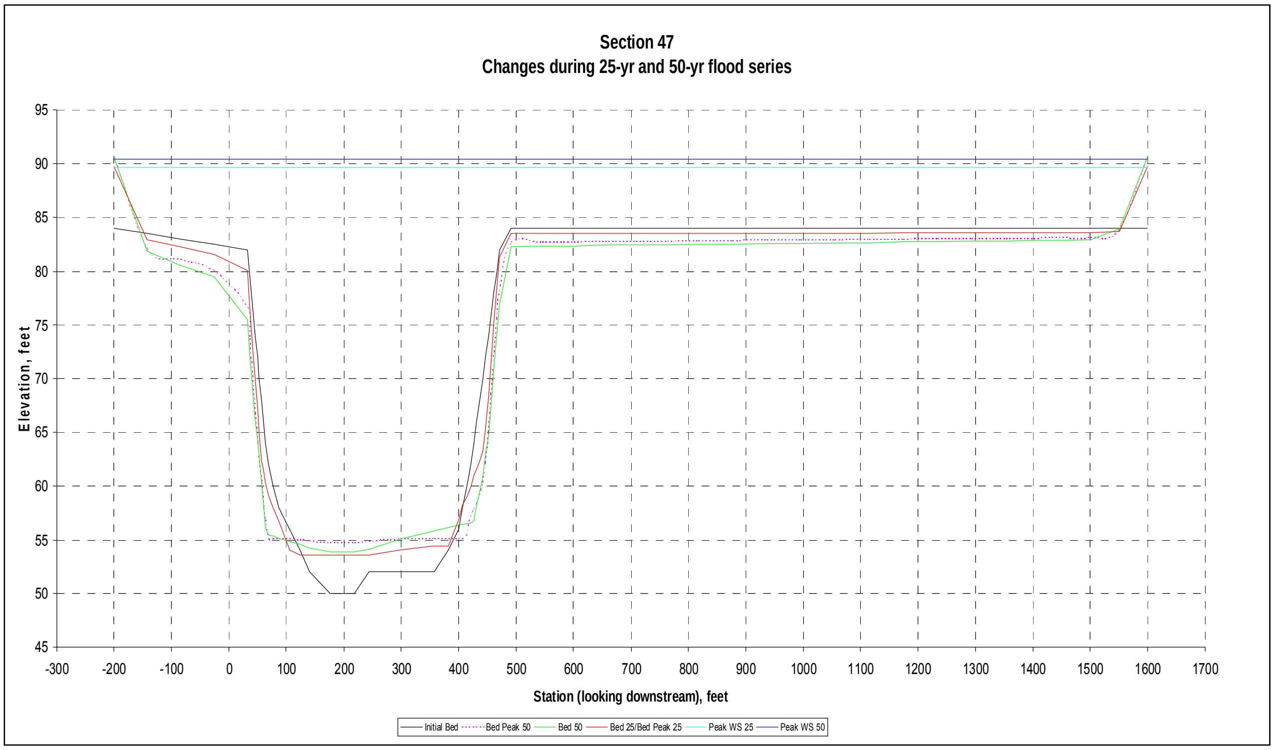

Section 46
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

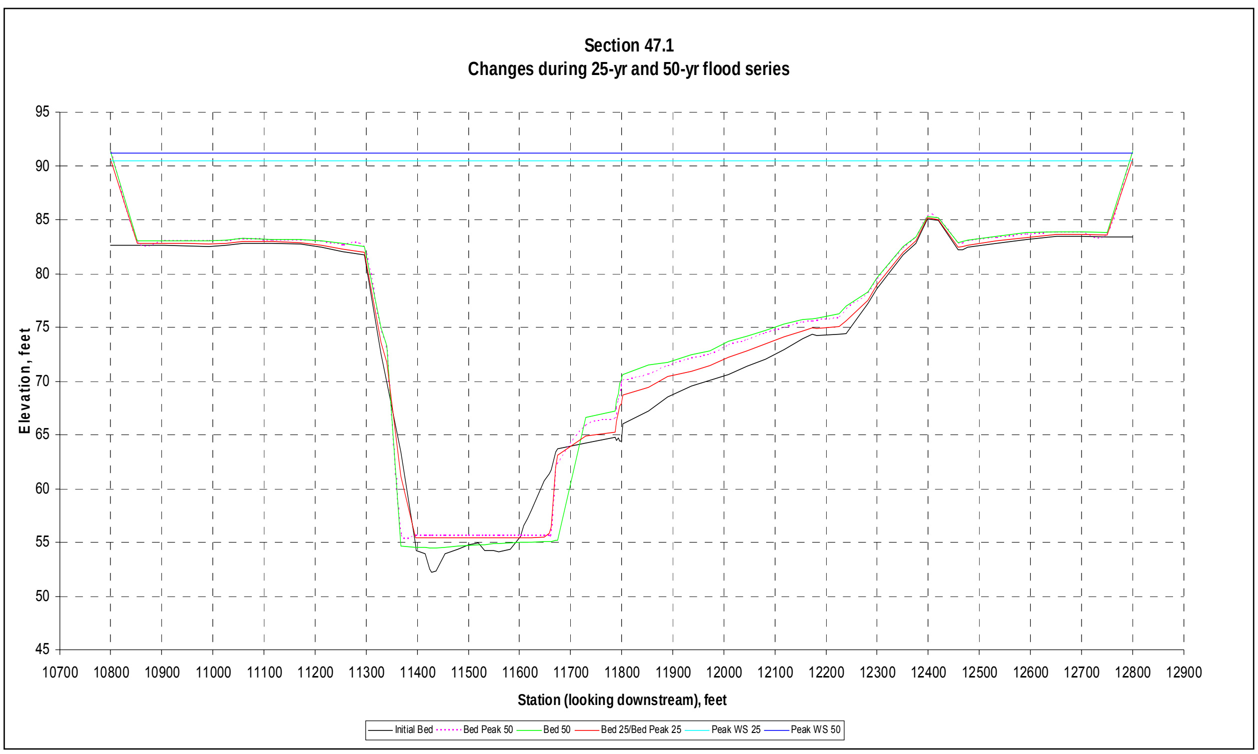

Section 46.2
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

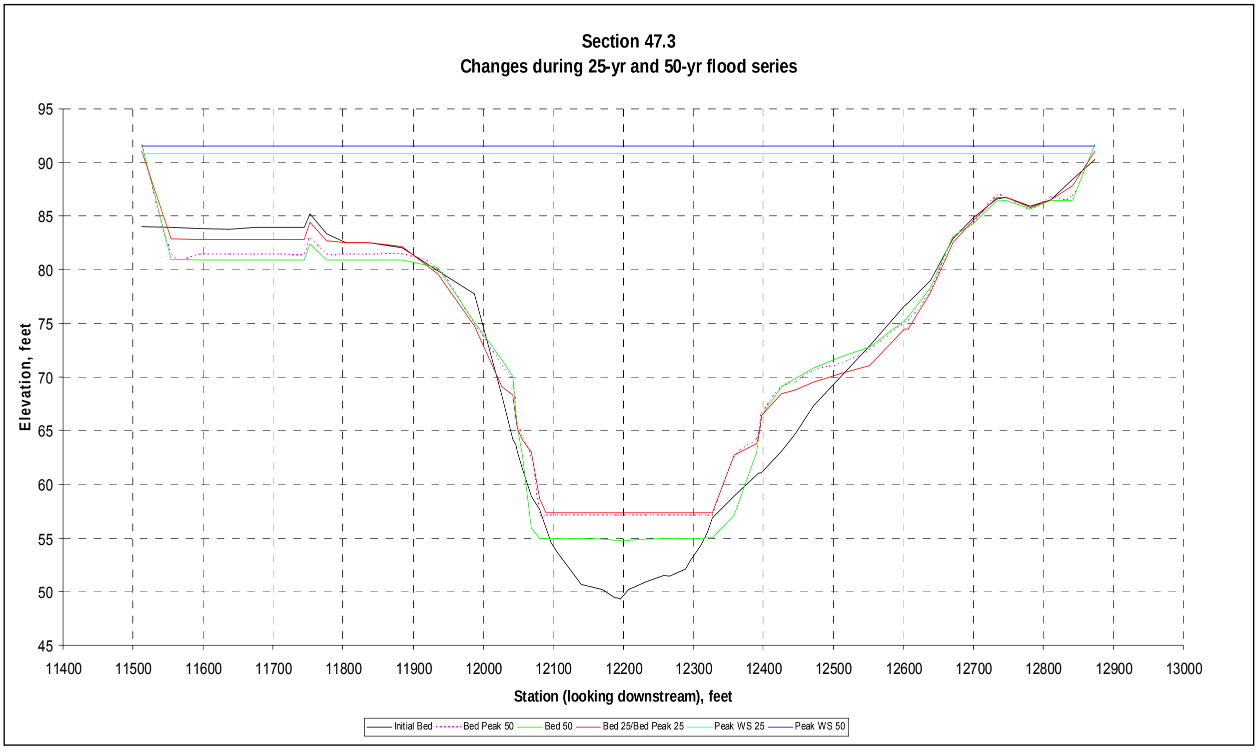

Section 46.3
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50


Section 46.6
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

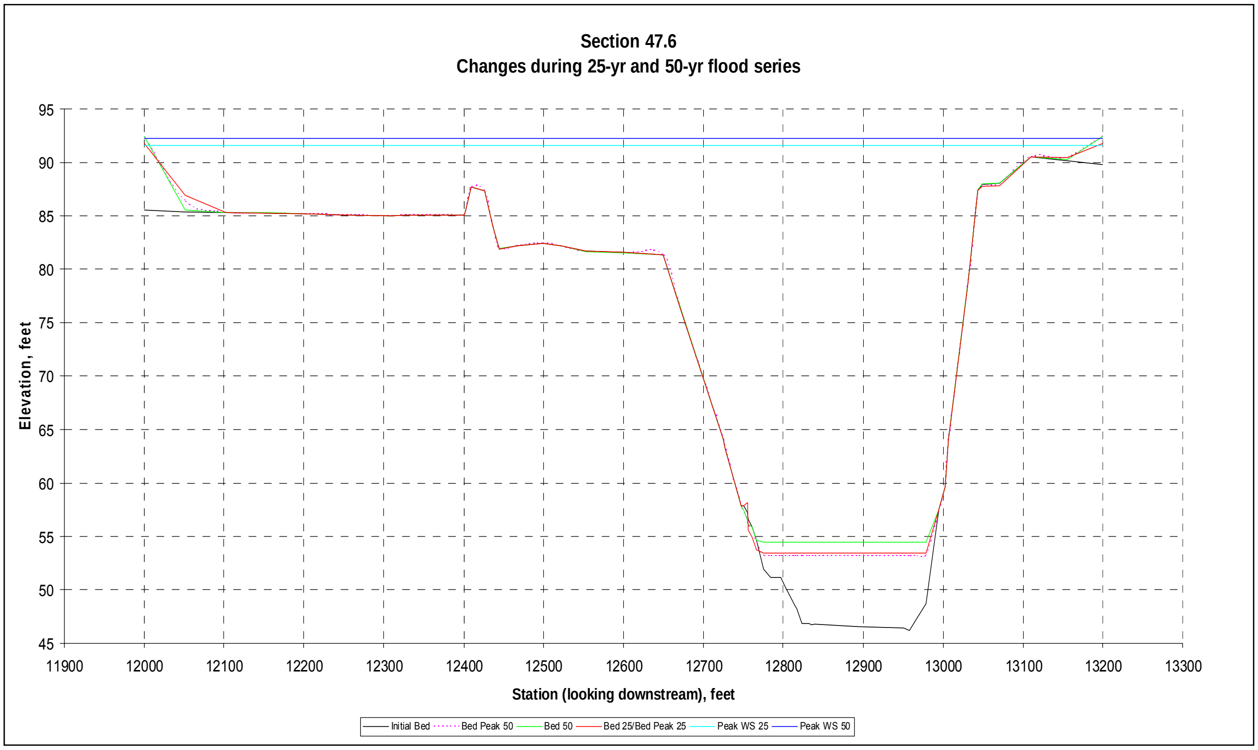

Section 46.8
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

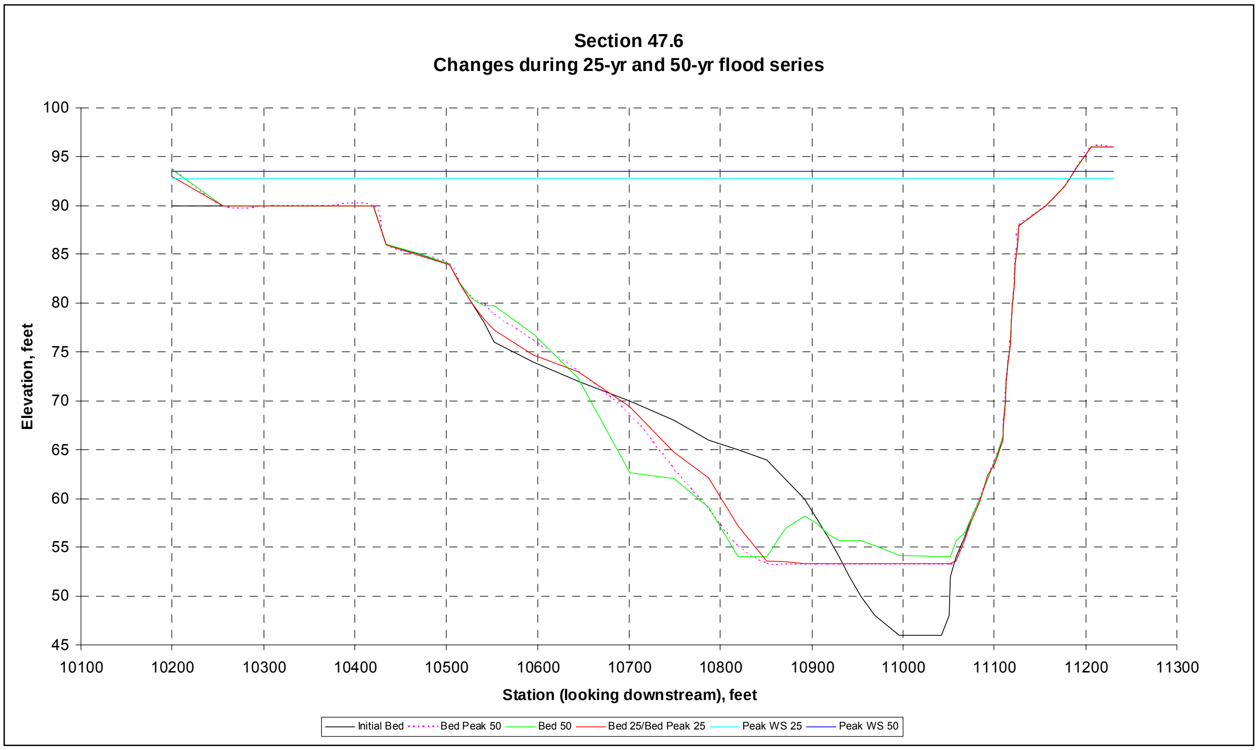

Section 47
Changes during 25-yr and 50-yr flood series
Elevation, feet
95
90
85
80
75
70
65
60
55
50
45
-300
-200
-100
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

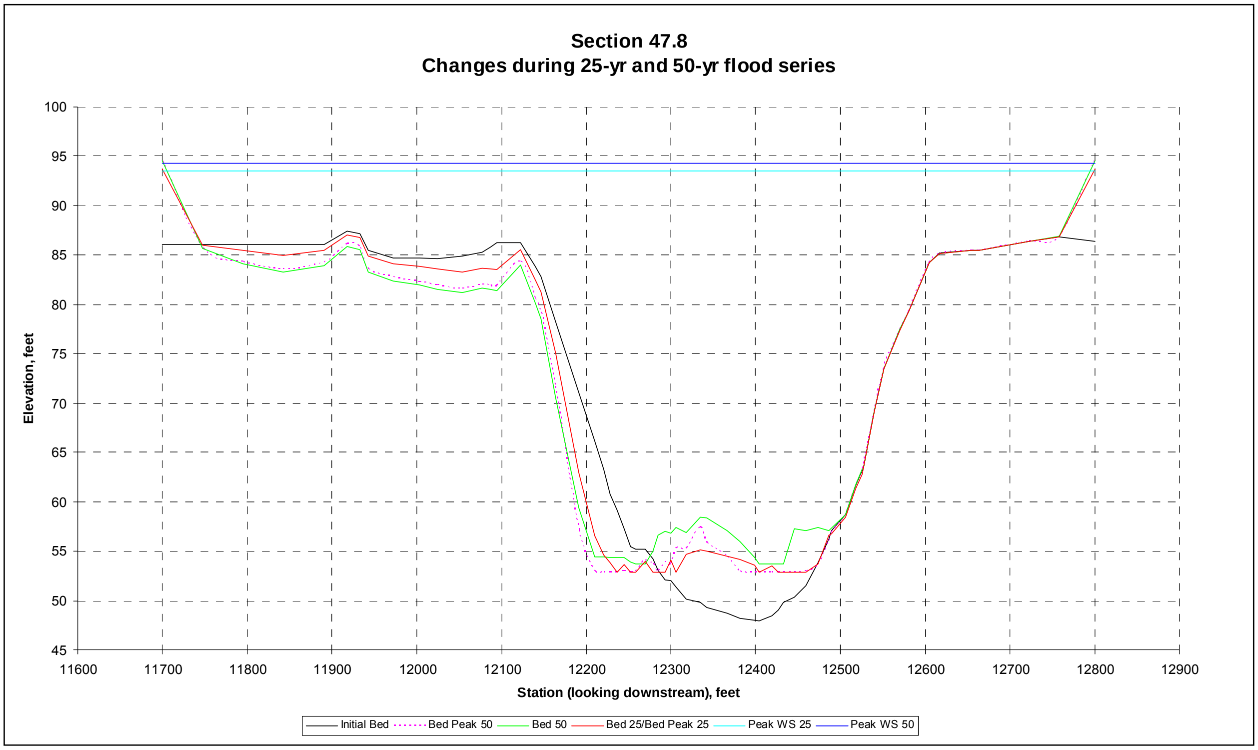

Section 47.1
Changes during 25-yr and 50-yr flood series
Elevation, feet
95
90
85
80
75
70
65
60
55
50
45
10700
10800
10900
11000
11100
11200
11300
11400
11500
11600
11700
11800
11900
12000
12100
12200
12300
12400
12500
12600
12700
12800
12900
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

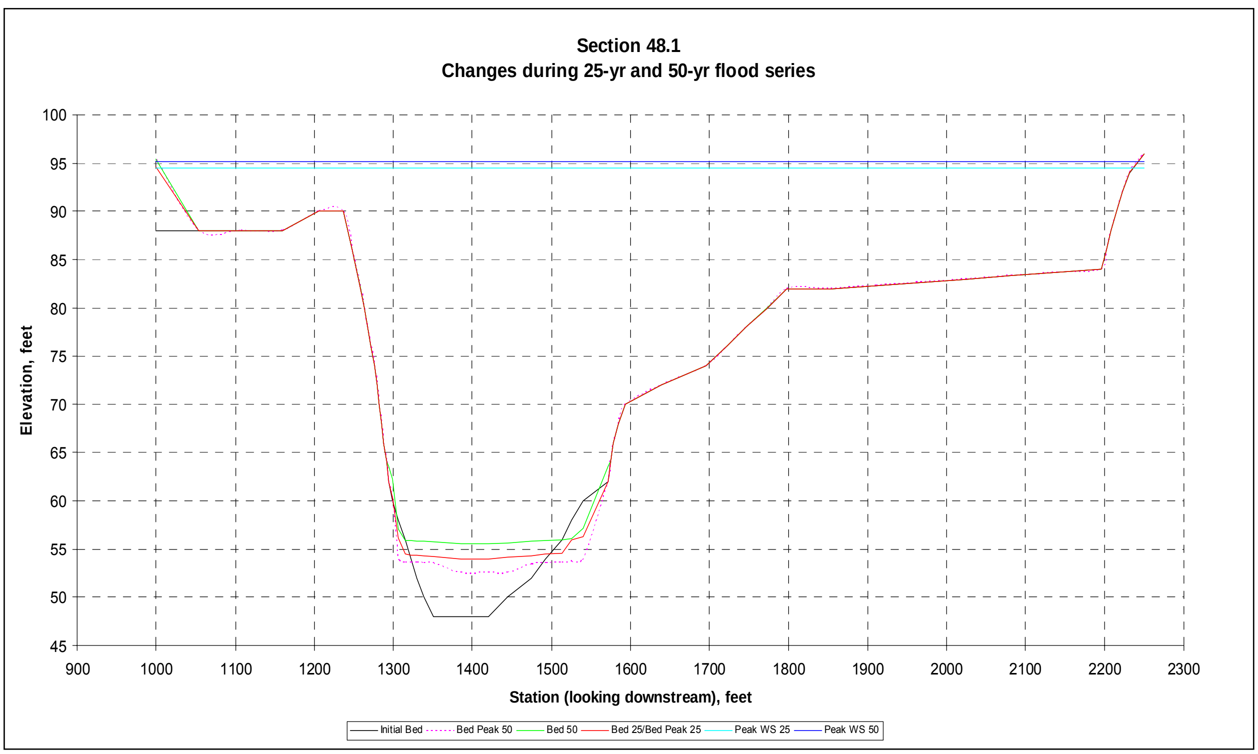

Section 47.3
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

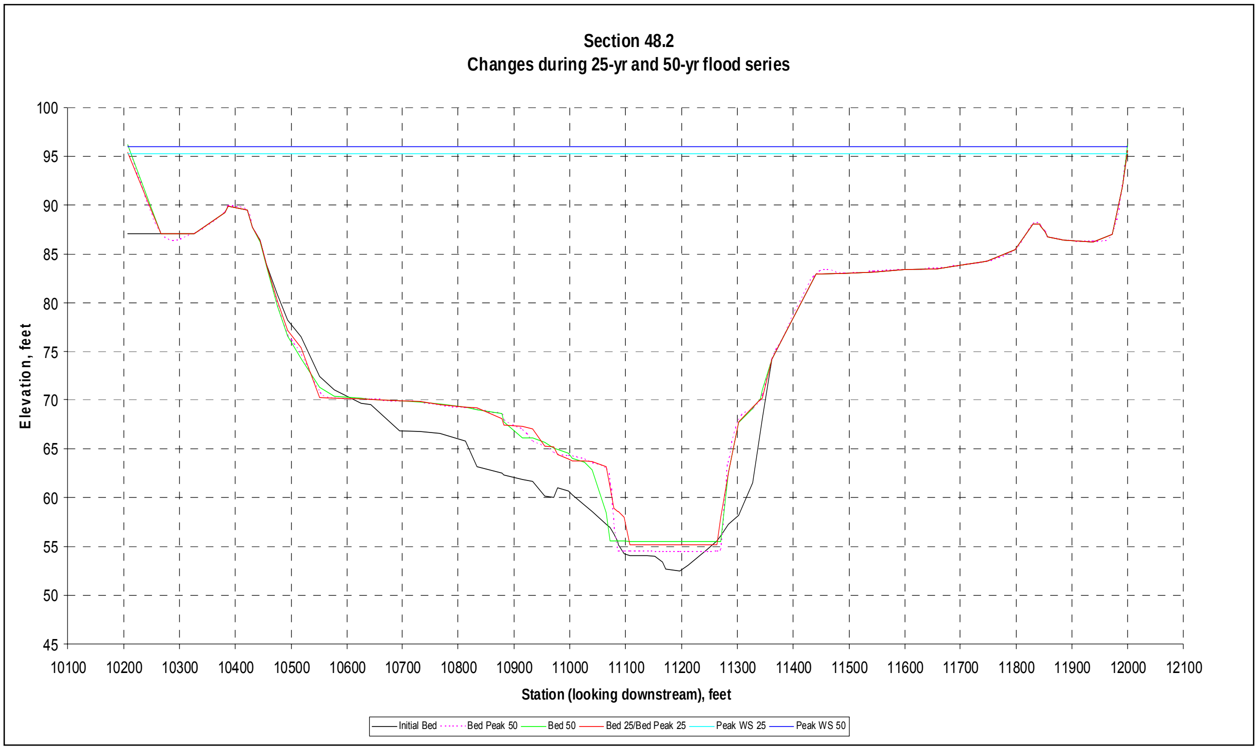

Section 47.5
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50


Section 47.6
Changes during 25-yr and 50-yr flood series
Elevation, feet
95
90
85
80
75
70
65
60
55
50
45
11900
12000
12100
12200
12300
12400
12500
12600
12700
12800
12900
13000
13100
13200
13300
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

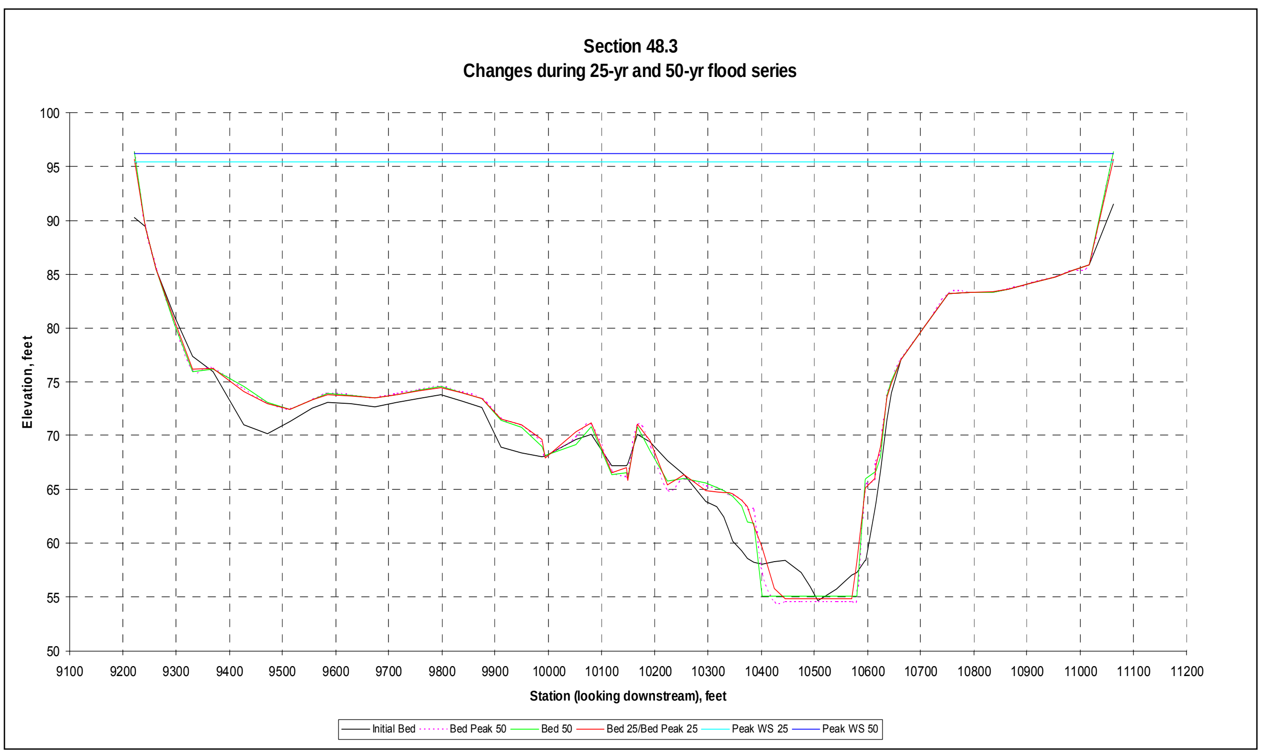

Section 47.6
Changes during 25-yr and 50-yr flood series
Elevation, feet
100
95
90
85
80
75
70
65
60
55
50
45
10100
10200
10300
10400
10500
10600
10700
10800
10900
11000
11100
11200
11300
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50


Section 47.8
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
100
95
90
85
80
75
70
65
60
55
50
45
11600
11700
11800
11900
12000
12100
12200
12300
12400
12500
12600
12700
12800
12900
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

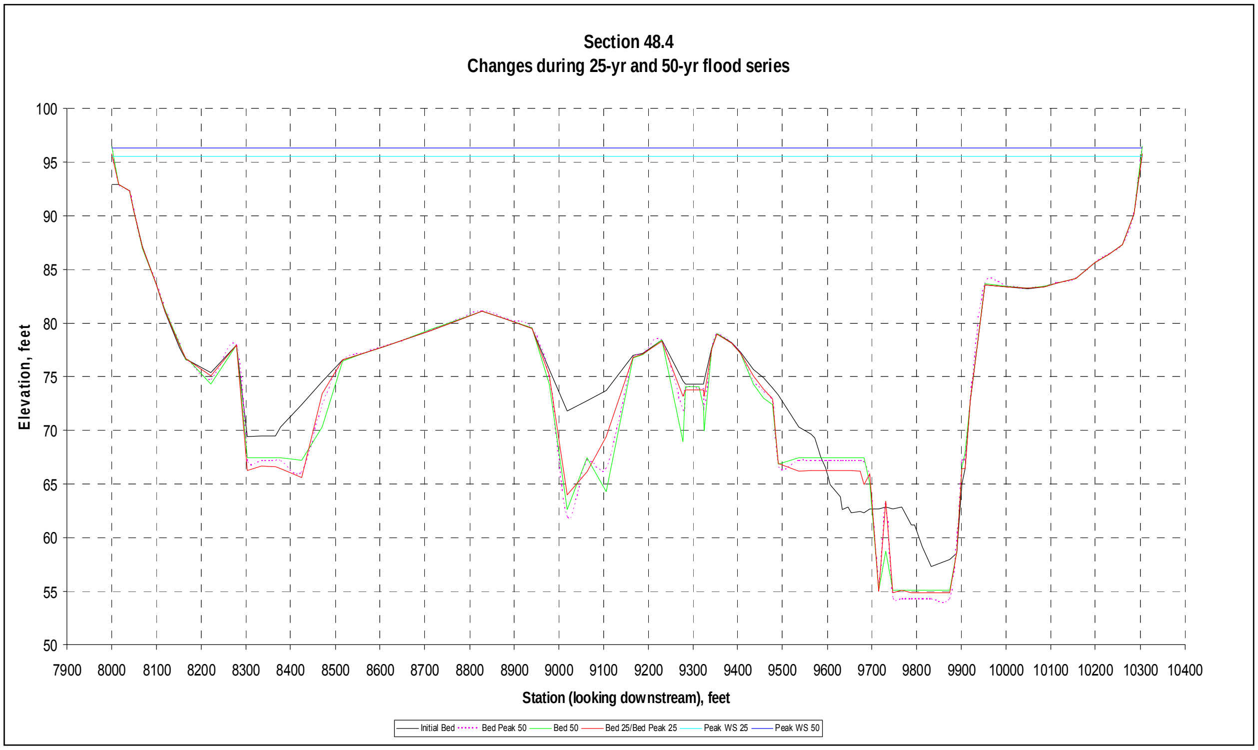

Section 48.1
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
100
95
90
85
80
75
70
65
60
55
50
45
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
2100
2200
2300
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50



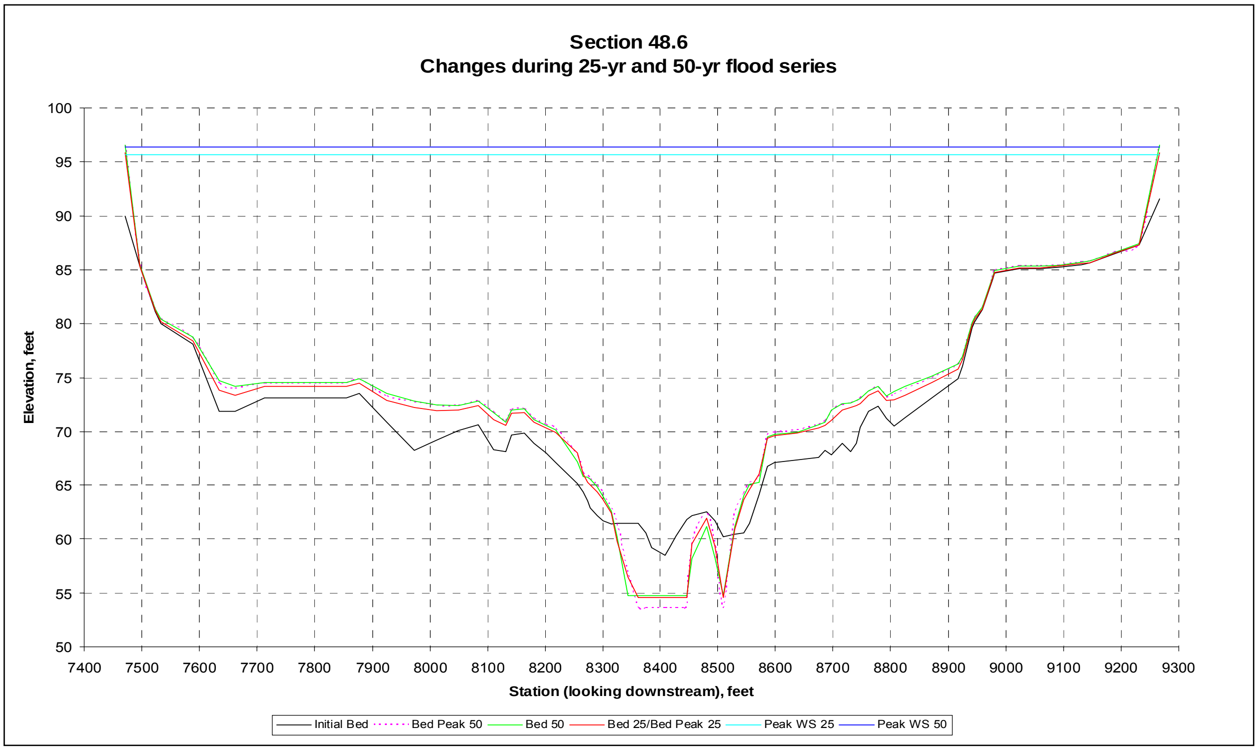
Section 48.2
Changes during 25-yr and 50-yr flood series
Elevation, feet
100
95
90
85
80
75
70
65
60
55
50
45
10100
10200
10300
10400
10500
10600
10700
10800
10900
11000
11100
11200
11300
11400
11500
11600
11700
11800
11900
12000
12100
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50



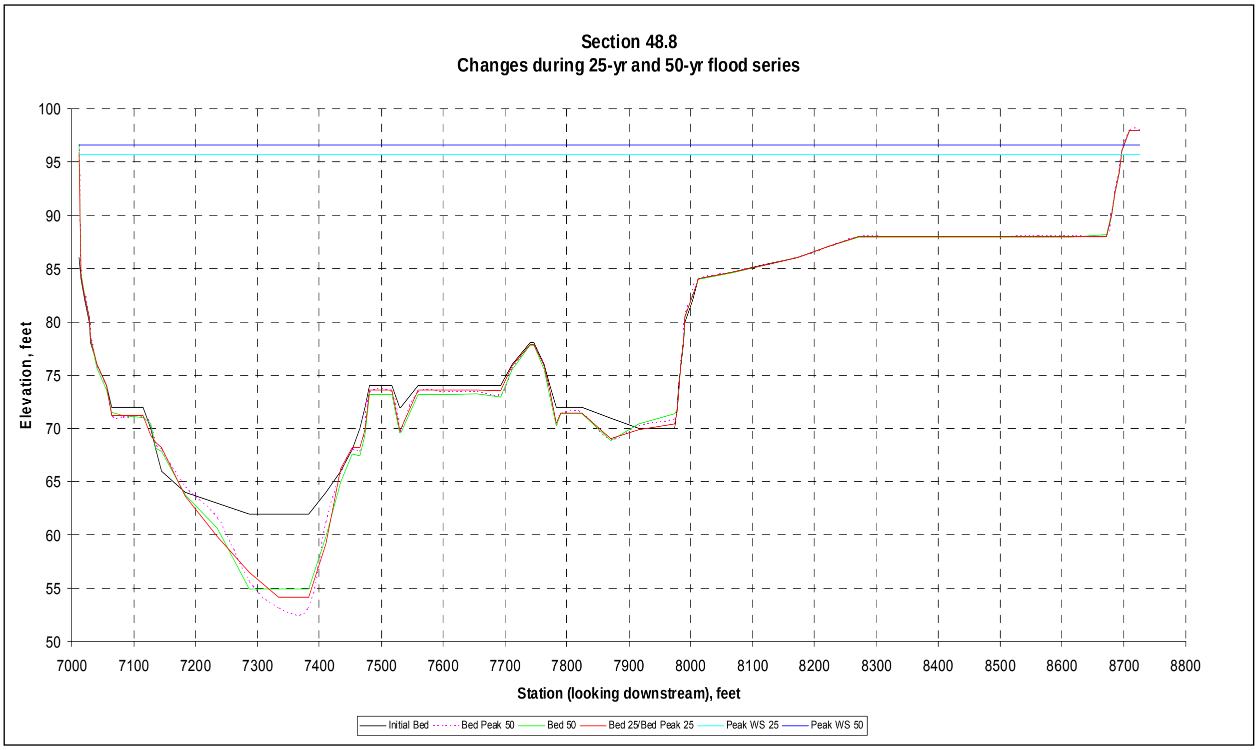
Section 48.3
Changes during 25-yr and 50-yr flood series
Elevation, feet
100
95
90
85
80
75
70
65
60
55
50
9100
9200
9300
9400
9500
9600
9700
9800
9900
10000
10100
10200
10300
10400
10500
10600
10700
10800
10900
11000
11100
11200
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

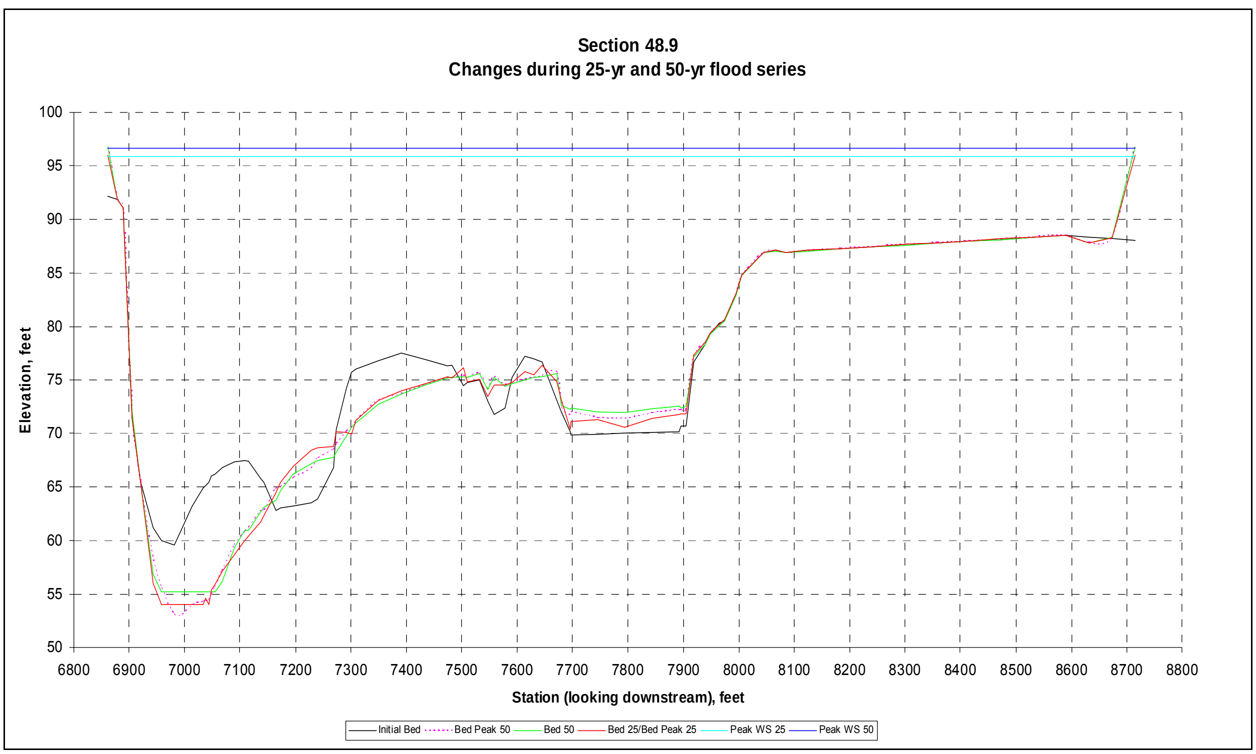


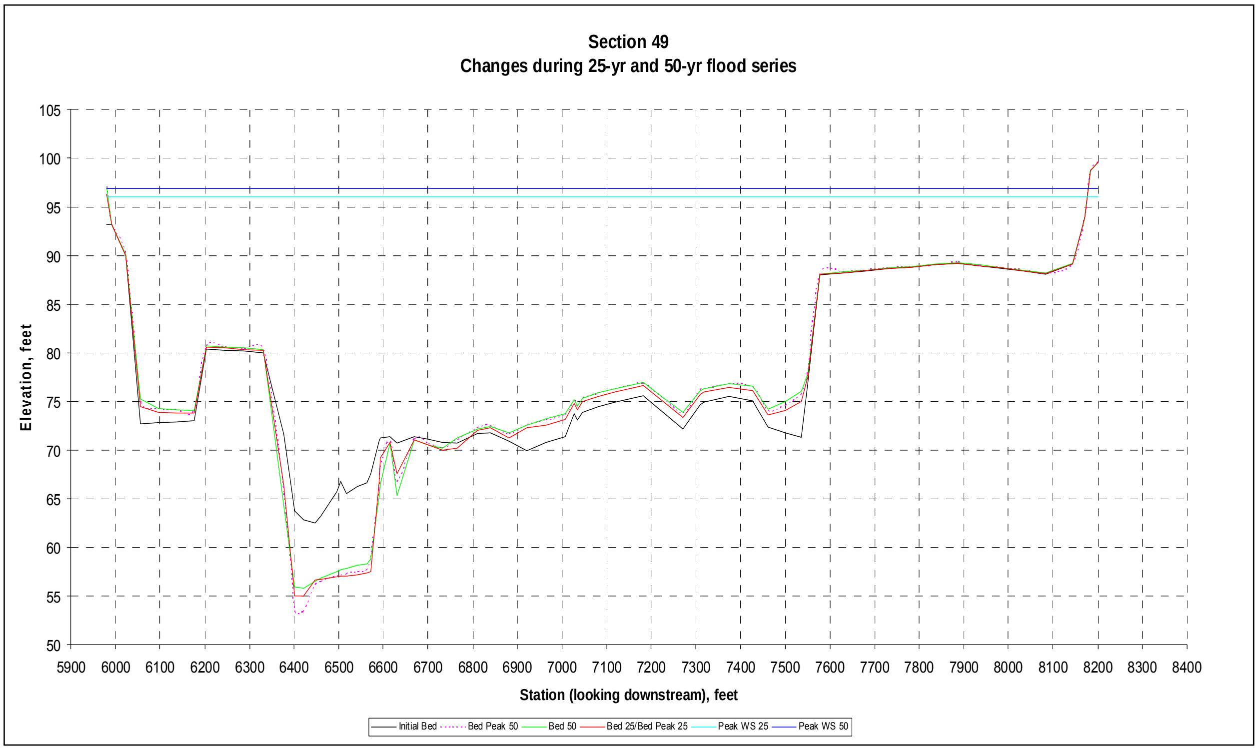
Section 48.4
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

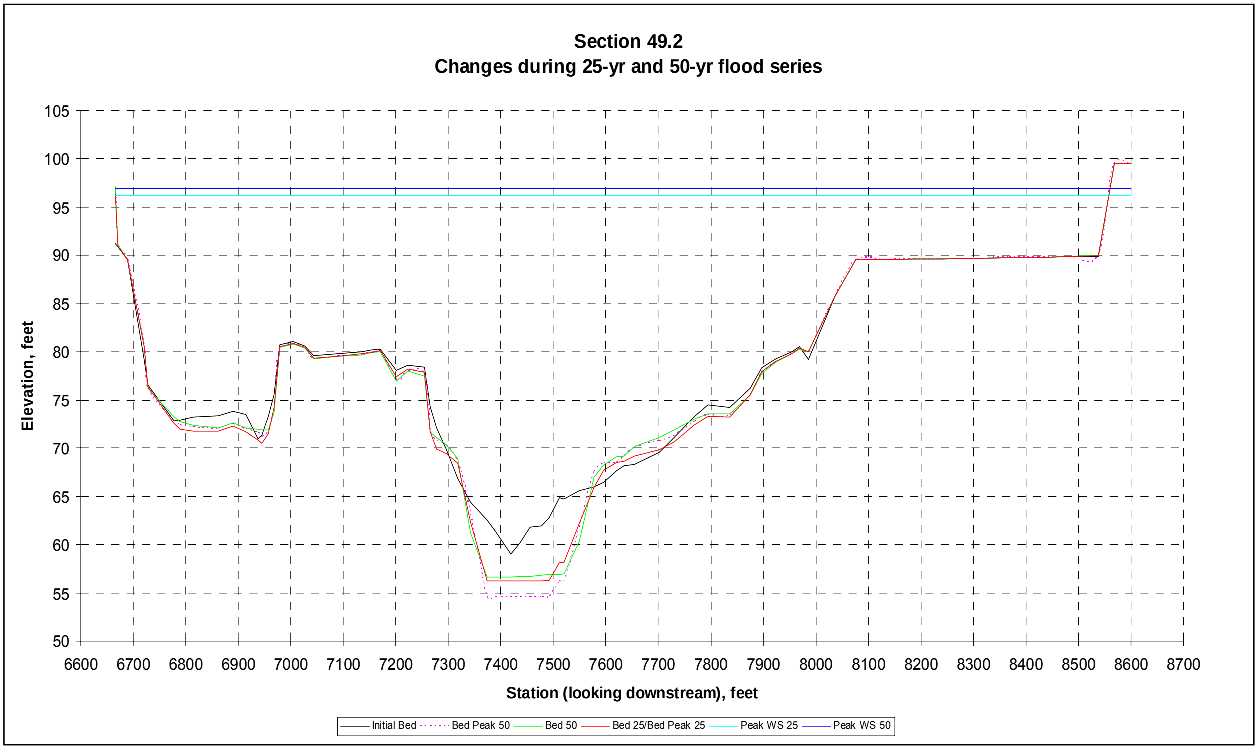


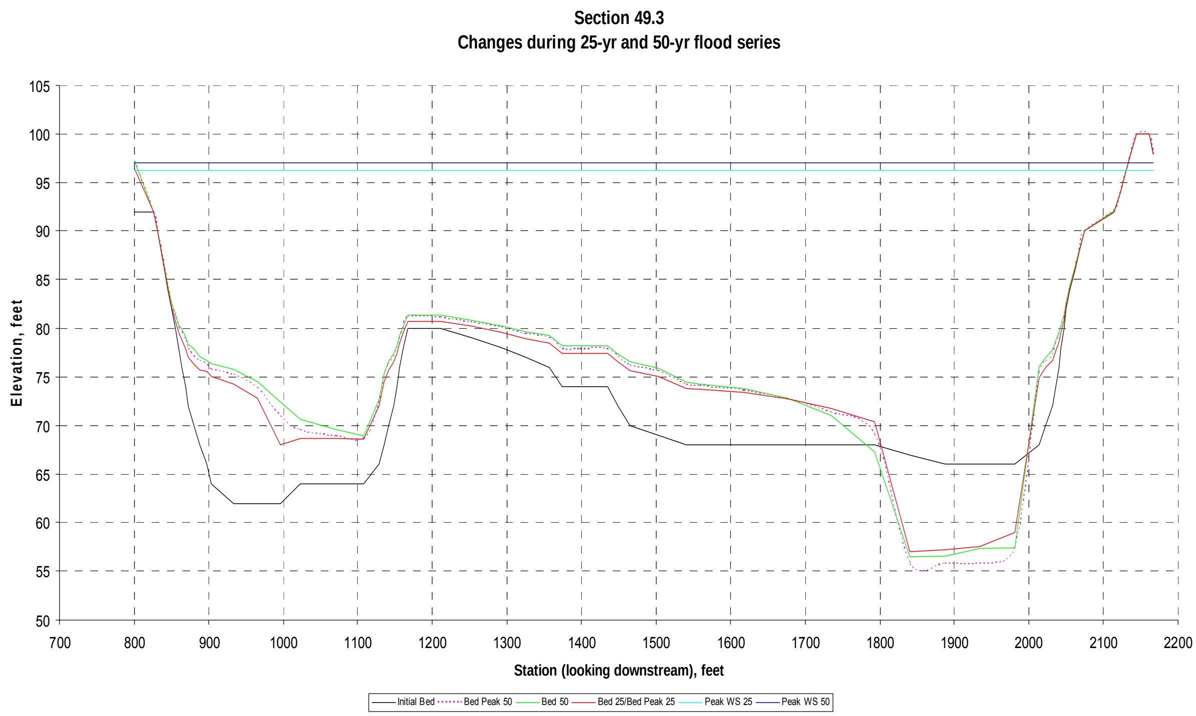
Section 48.6
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50


Section 48.8
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
100
95
90
85
80
75
70
65
60
55
50
7000
7100
7200
7300
7400
7500
7600
7700
7800
7900
8000
8100
8200
8300
8400
8500
8600
8700
8800
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

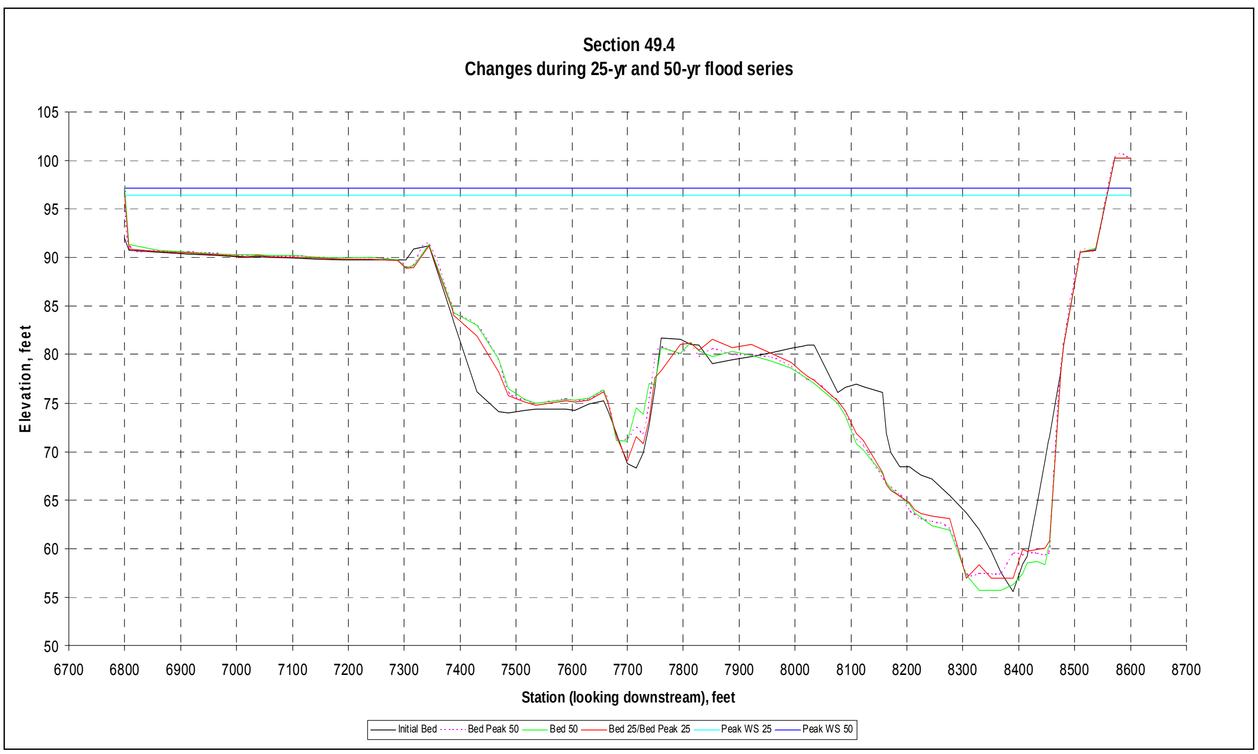

Section 48.9
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
100
95
90
85
80
75
70
65
60
55
50
6800
6900
7000
7100
7200
7300
7400
7500
7600
7700
7800
7900
8000
8100
8200
8300
8400
8500
8600
8700
8800
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50


Section 49
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

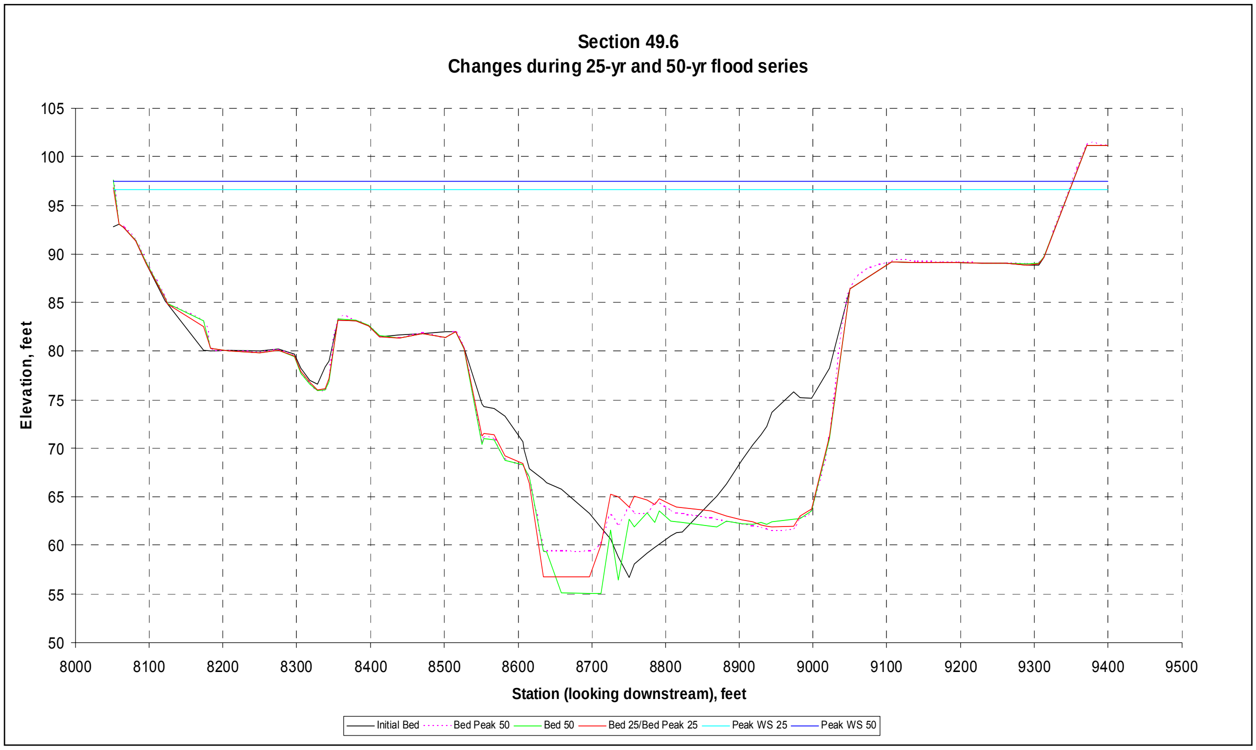

Section 49.2
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

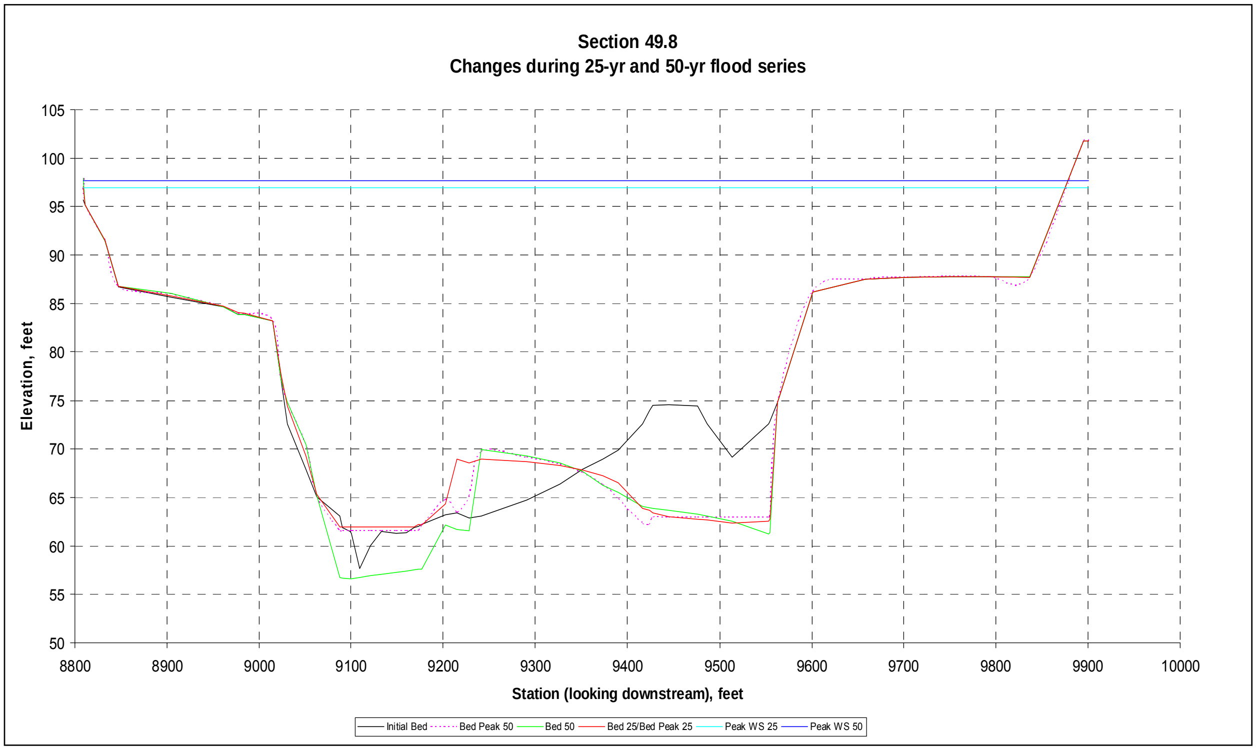


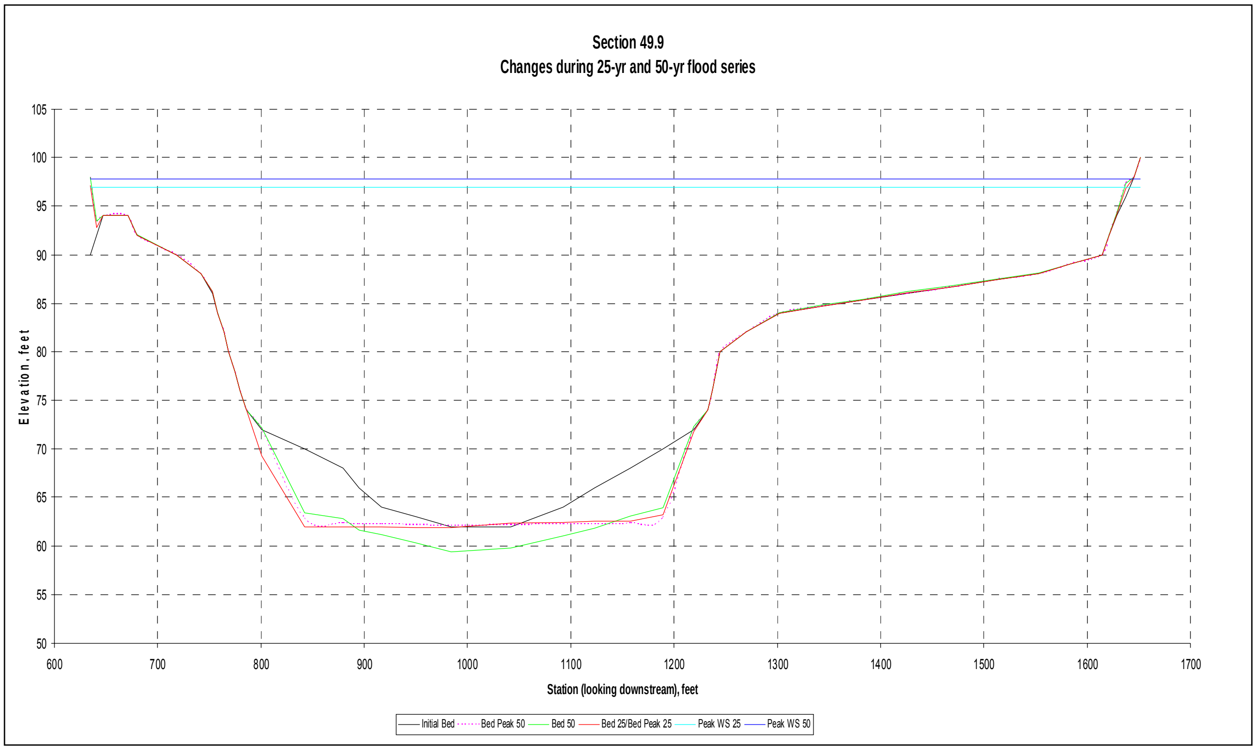
Section 49.3
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

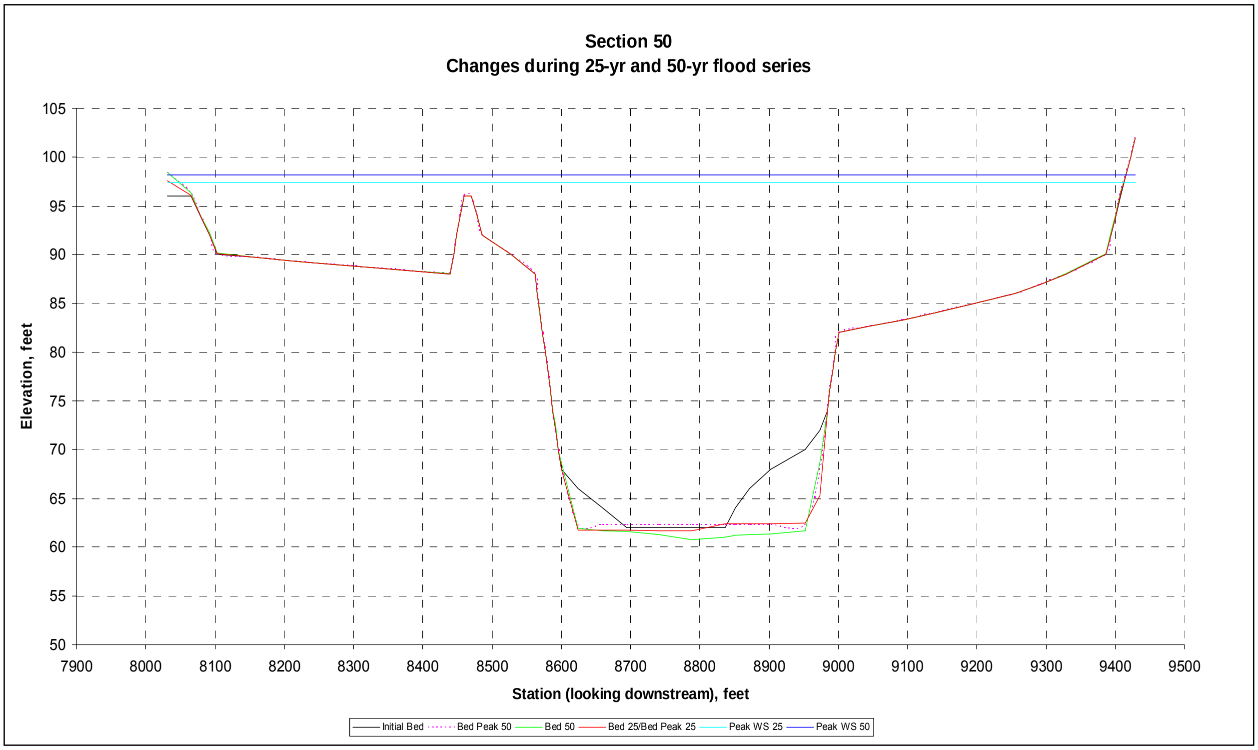


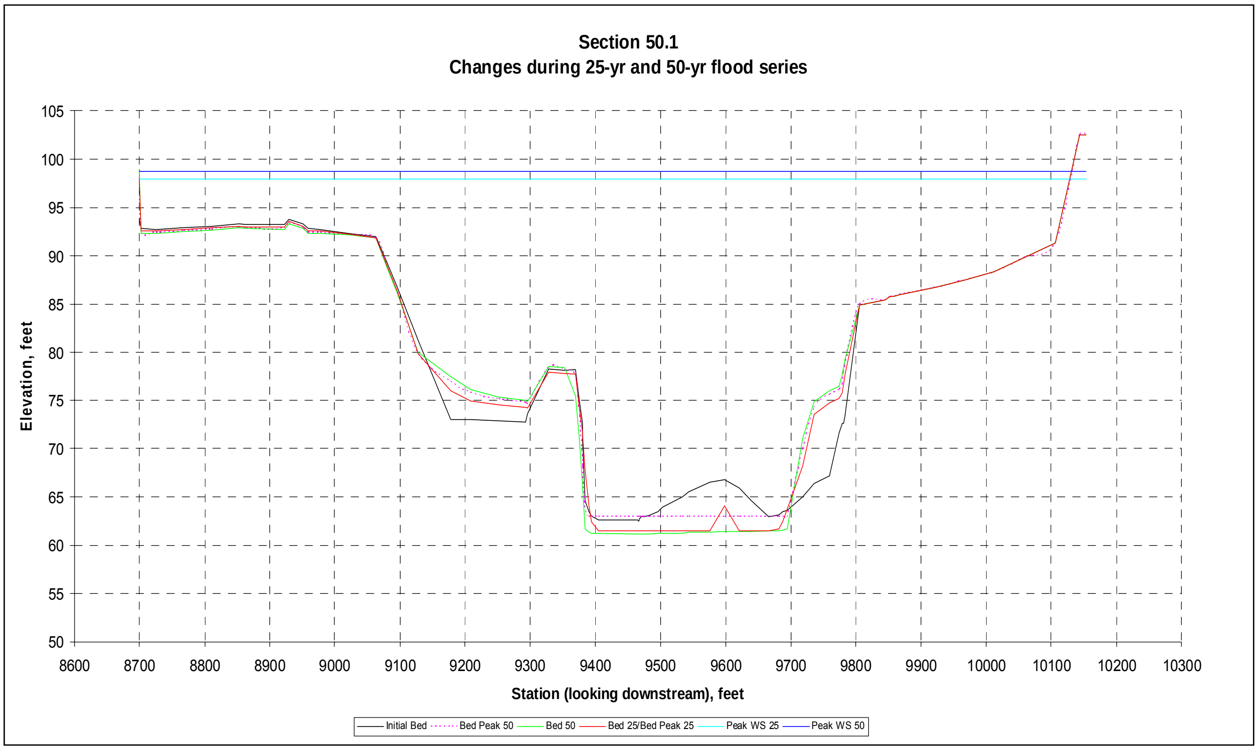
Section 49.4
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

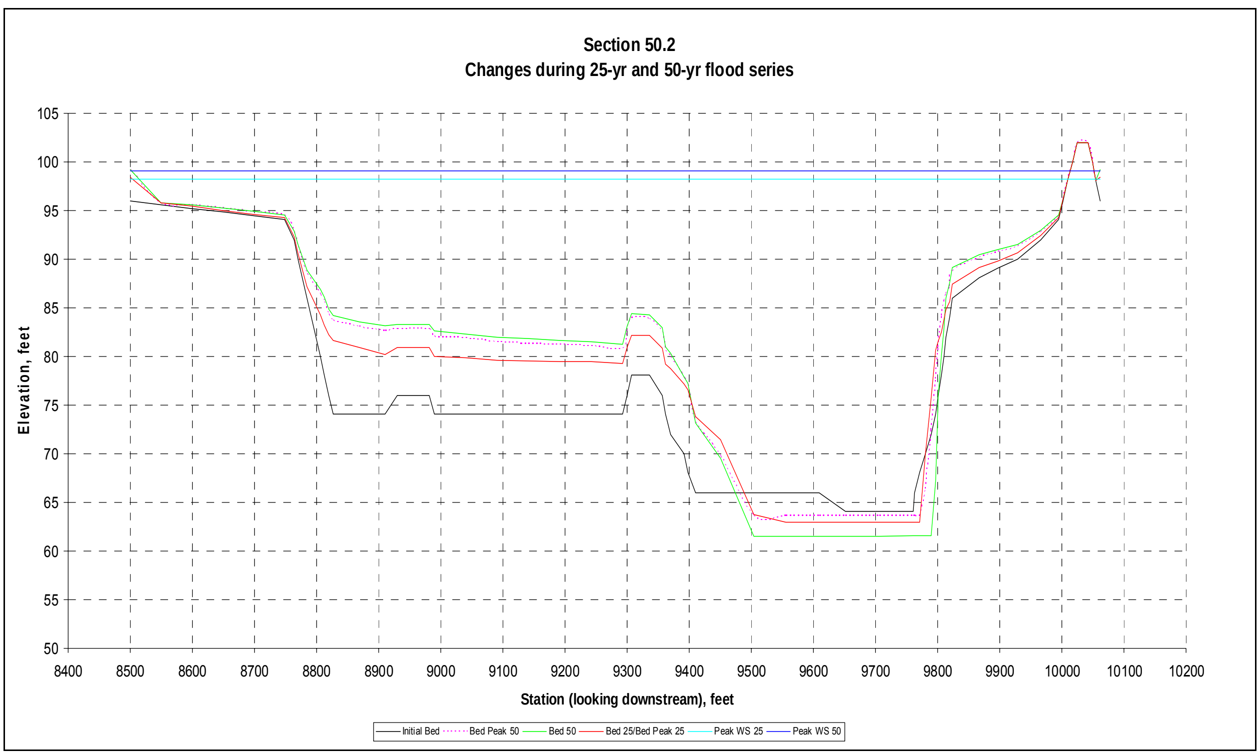

Section 49.6
Changes during 25-yr and 50-yr flood series
Elevation, feet
105
100
95
90
85
80
75
70
65
60
55
50
8000
8100
8200
8300
8400
8500
8600
8700
8800
8900
9000
9100
9200
9300
9400
9500
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

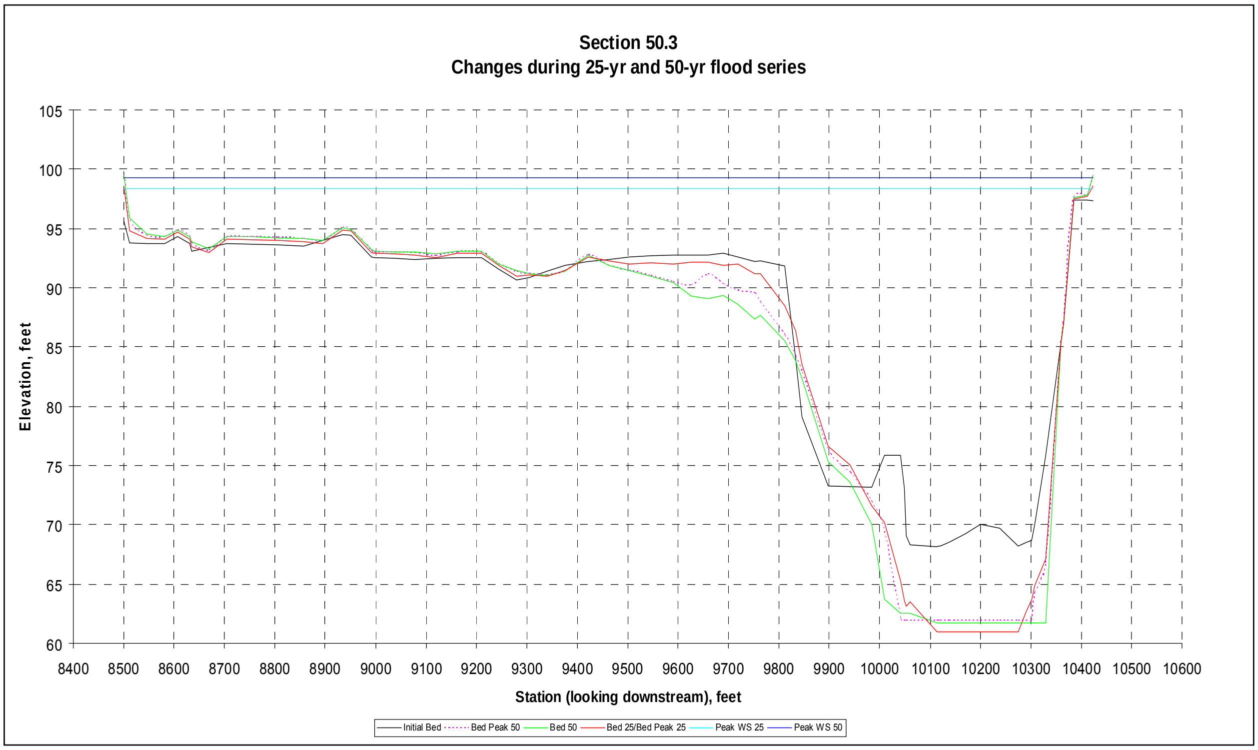

Section 49.8
Changes during 25-yr and 50-yr flood series
Elevation, feet
105
100
95
90
85
80
75
70
65
60
55
50
8800
8900
9000
9100
9200
9300
9400
9500
9600
9700
9800
9900
10000
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

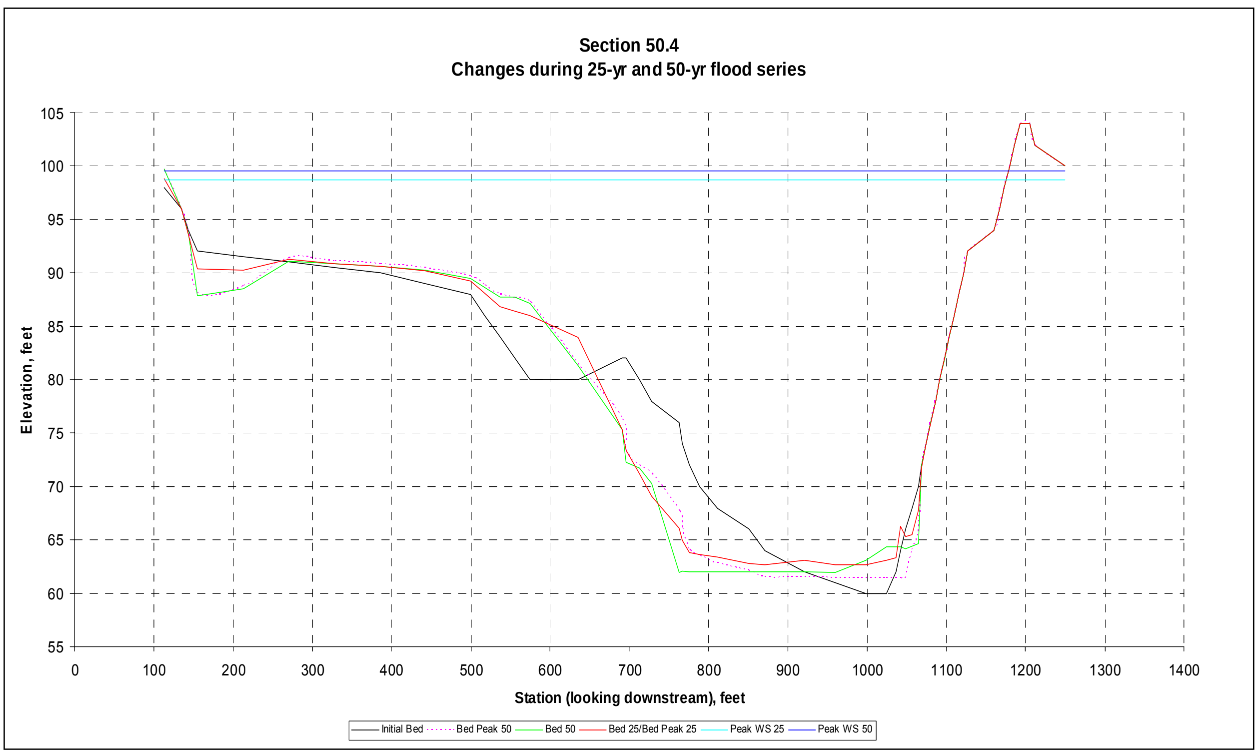

Section 49.9
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
105
100
95
90
85
80
75
70
65
60
55
50
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

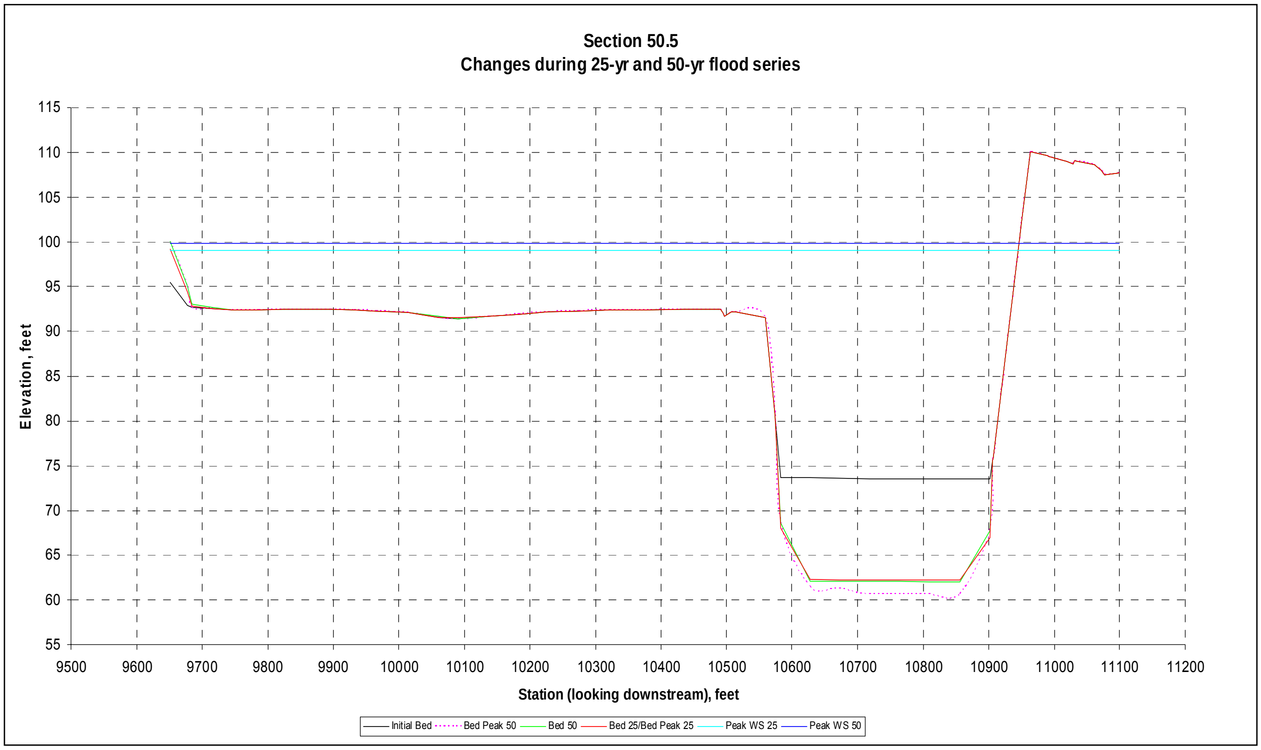

Section 50
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
105
100
95
90
85
80
75
70
65
60
55
50
7900
8000
8100
8200
8300
8400
8500
8600
8700
8800
8900
9000
9100
9200
9300
9400
9500
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

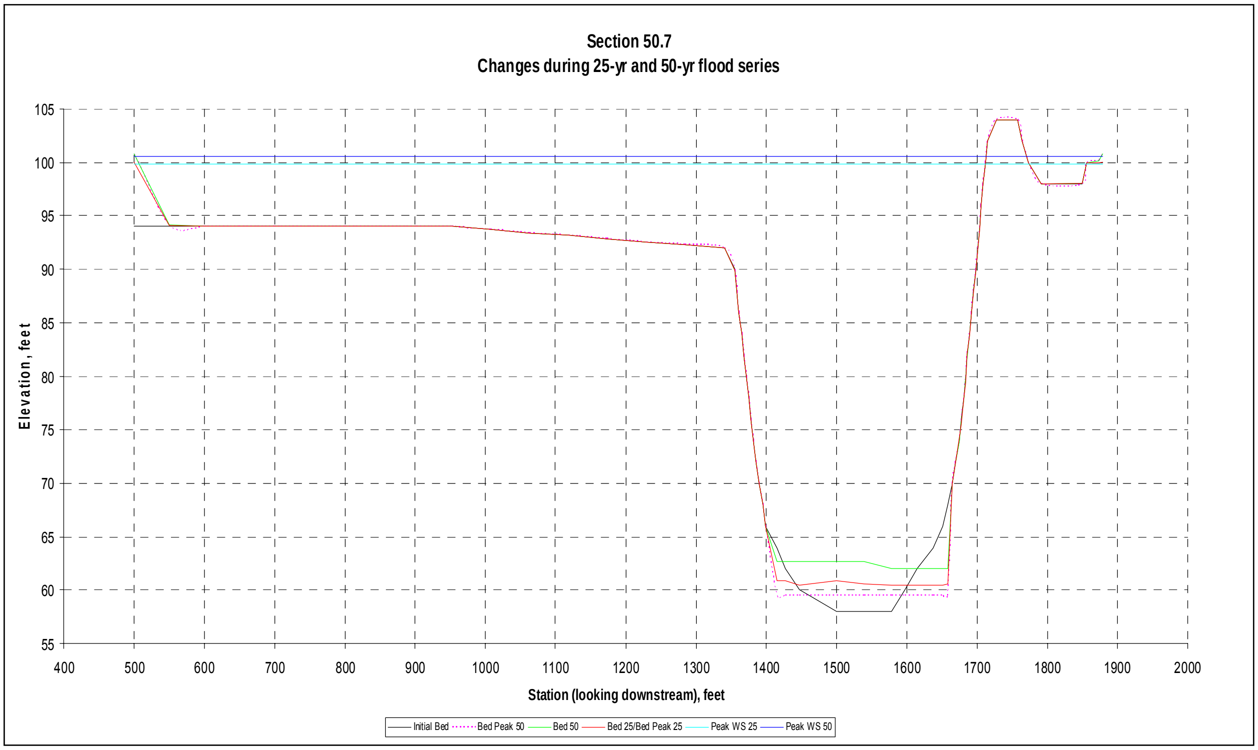

Section 50.1
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
105
100
95
90
85
80
75
70
65
60
55
50
8600
8700
8800
8900
9000
9100
9200
9300
9400
9500
9600
9700
9800
9900
10000
10100
10200
10300
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

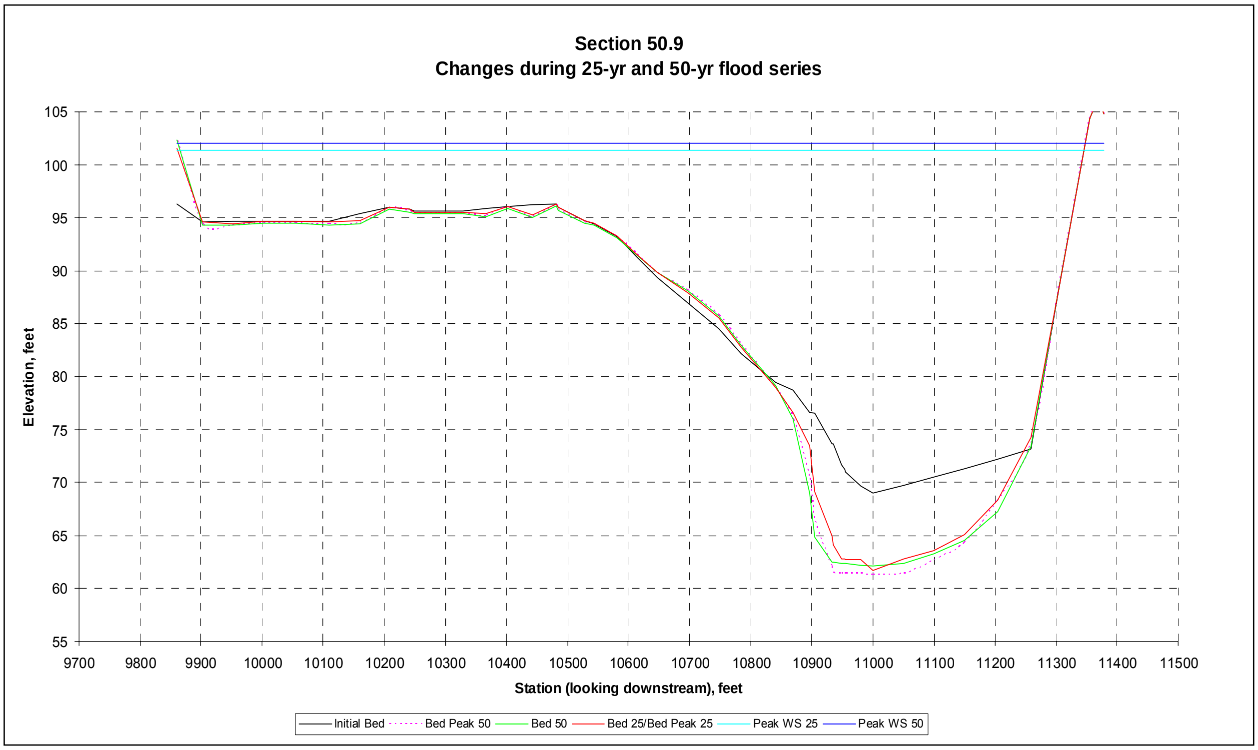

Section 50.2
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
105
100
95
90
85
80
75
70
65
60
55
50
8400
8500
8600
8700
8800
8900
9000
9100
9200
9300
9400
9500
9600
9700
9800
9900
10000
10100
10200
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

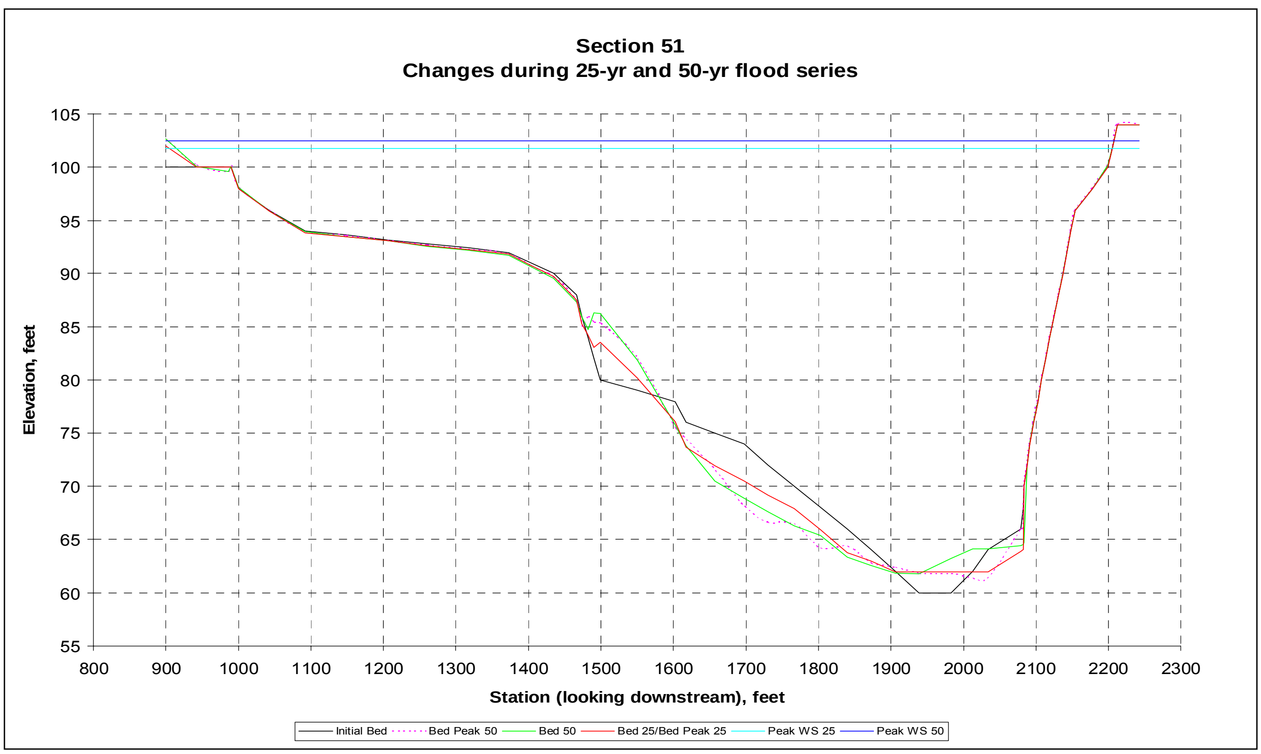

Section 50.3
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
105
100
95
90
85
80
75
70
65
60
8400
8500
8600
8700
8800
8900
9000
9100
9200
9300
9400
9500
9600
9700
9800
9900
10000
10100
10200
10300
10400
10500
10600
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

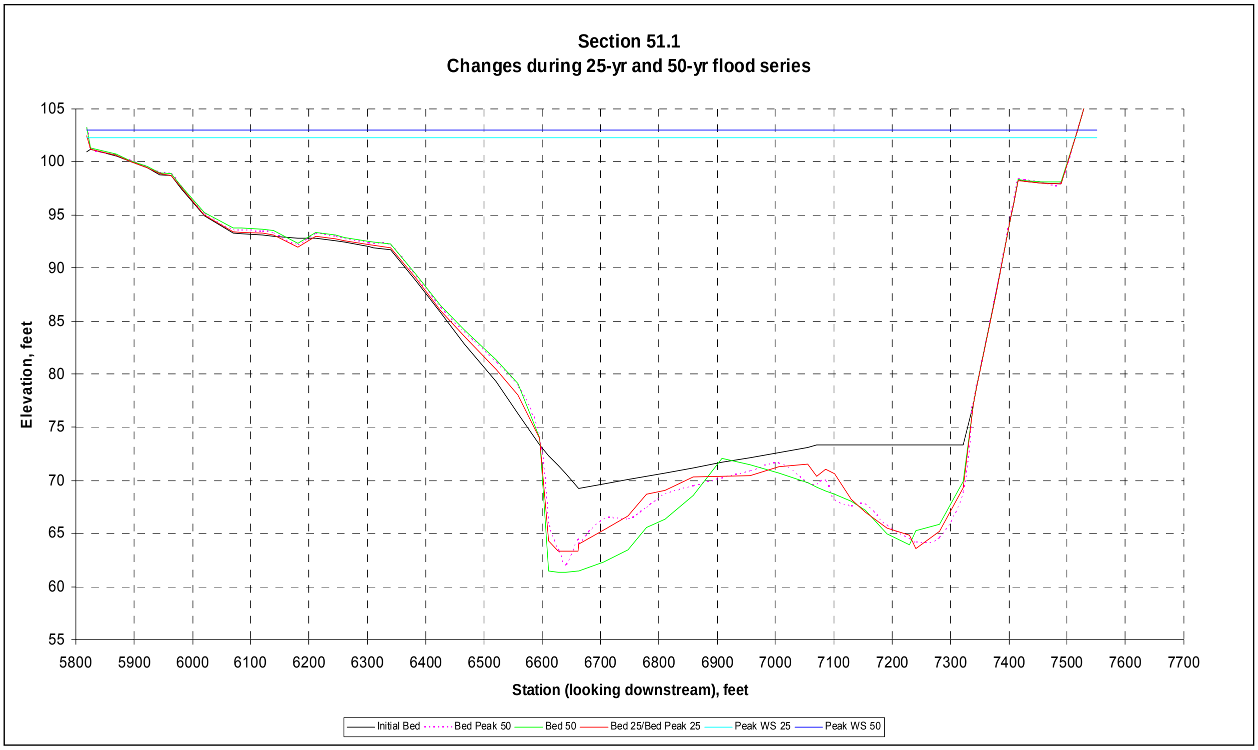

Section 50.4
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
105
100
95
90
85
80
75
70
65
60
55
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50


Section 50.5
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

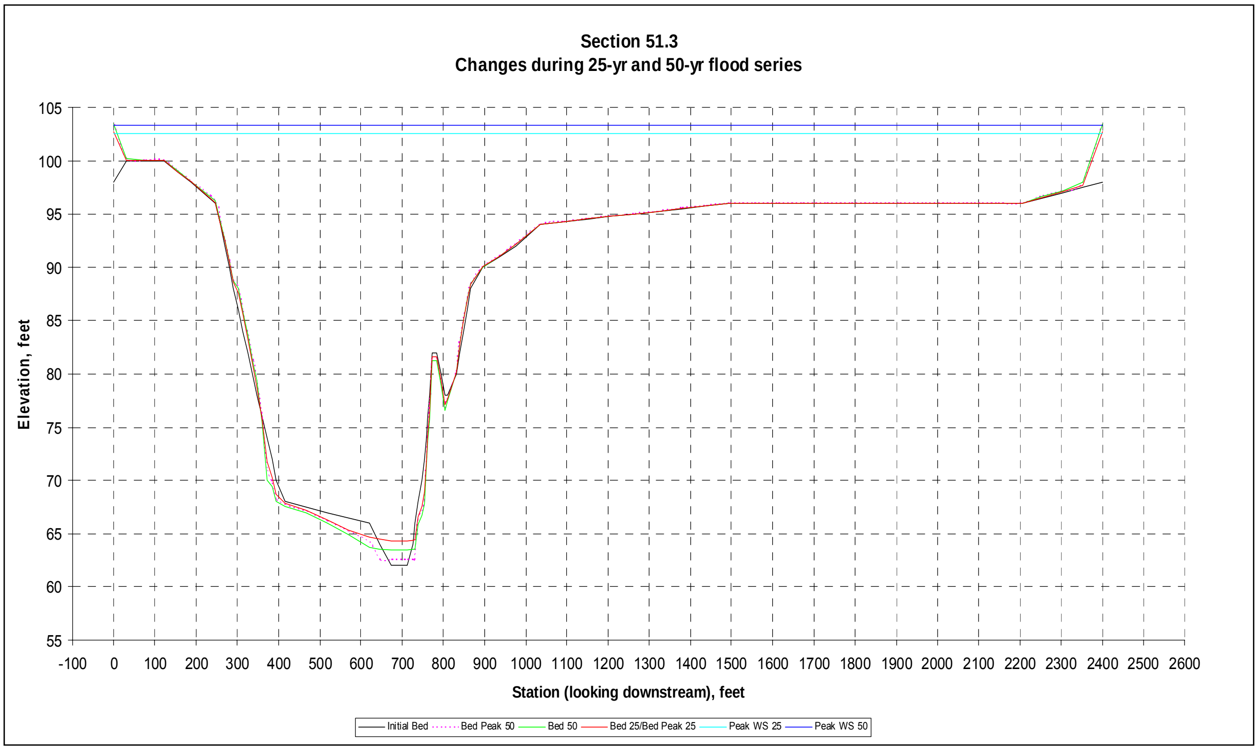

Section 50.7
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50


Section 50.9
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

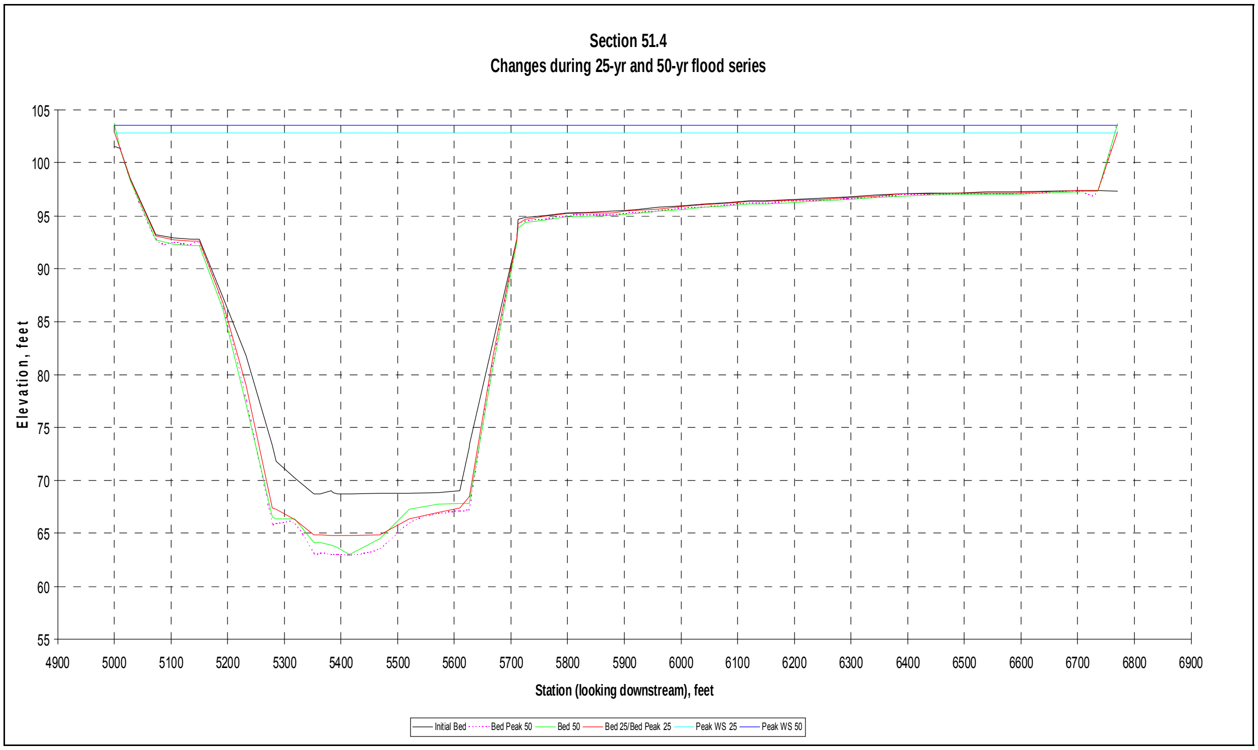

Section 51
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

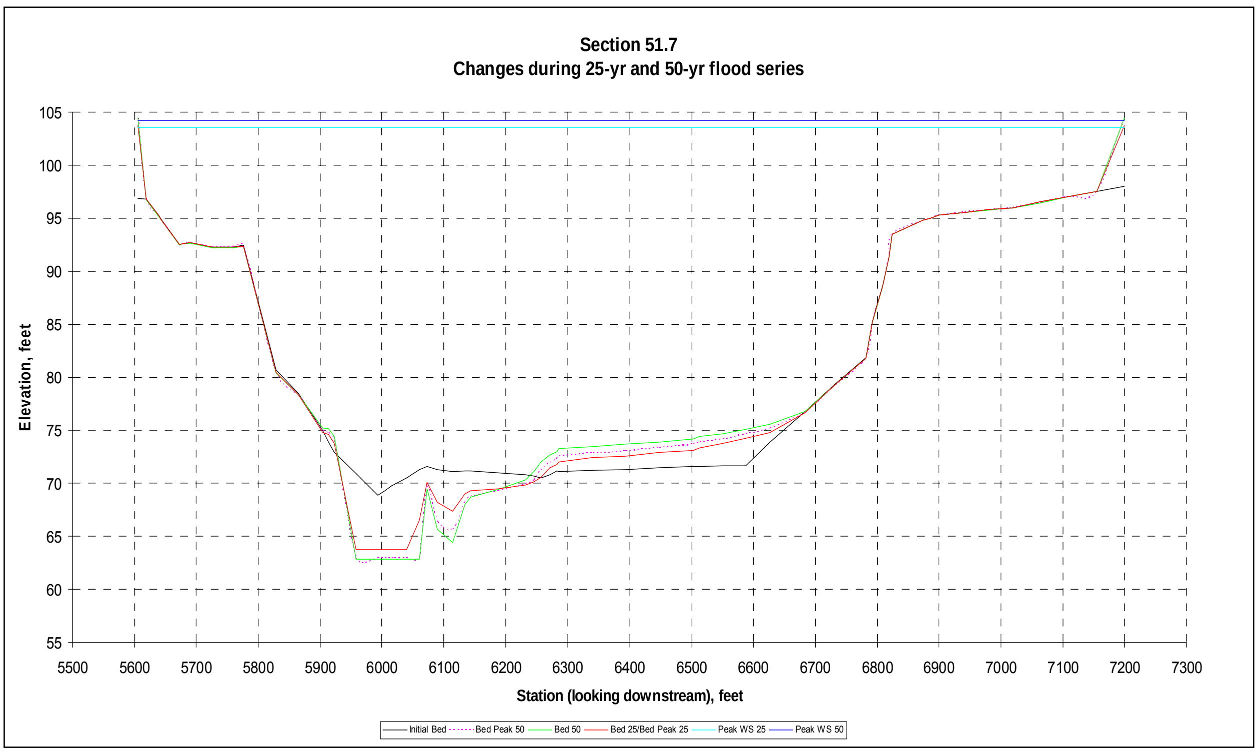


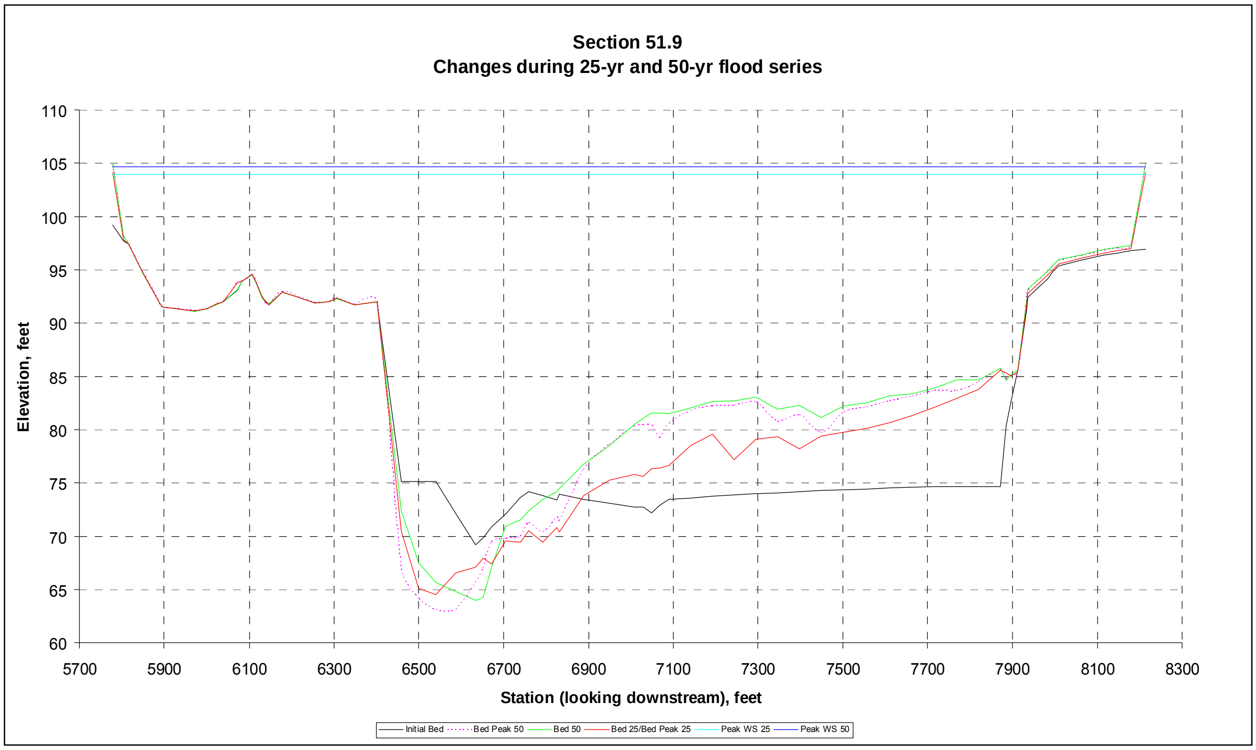
Section 51.1
Changes during 25-yr and 50-yr flood series
Elevation, feet
105
100
95
90
85
80
75
70
65
60
55
5800
5900
6000
6100
6200
6300
6400
6500
6600
6700
6800
6900
7000
7100
7200
7300
7400
7500
7600
7700
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

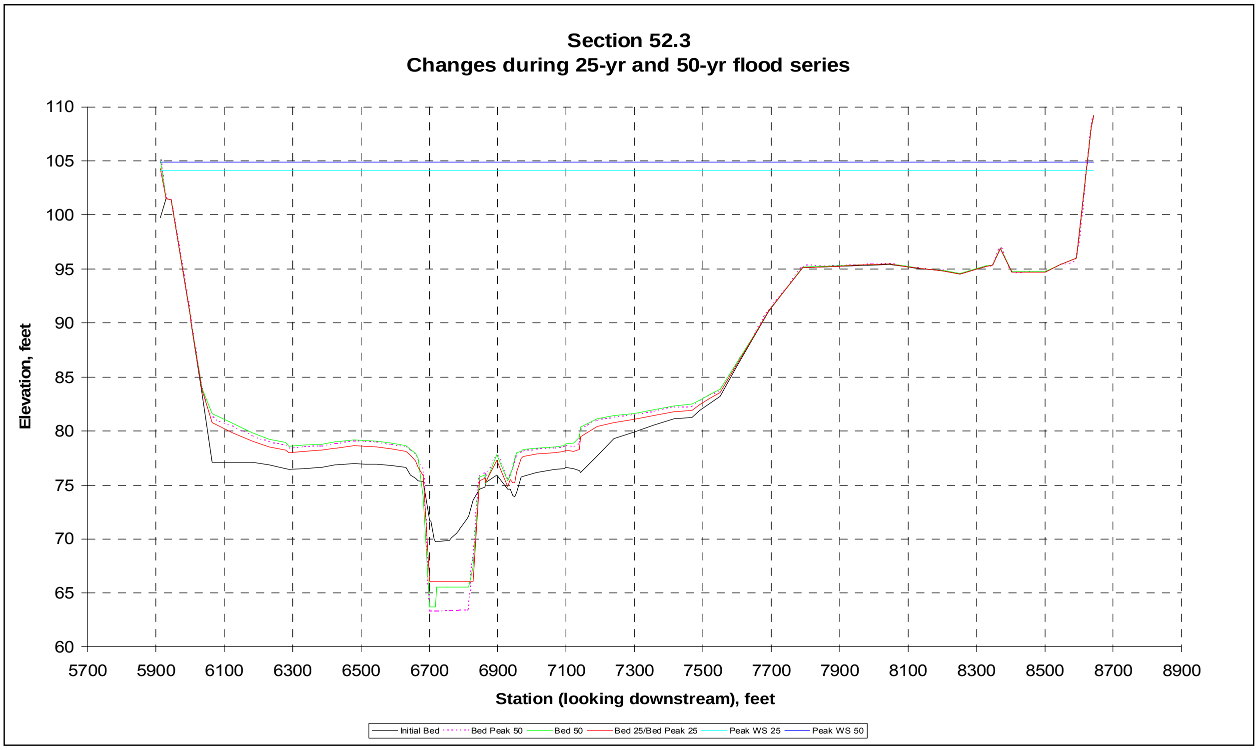


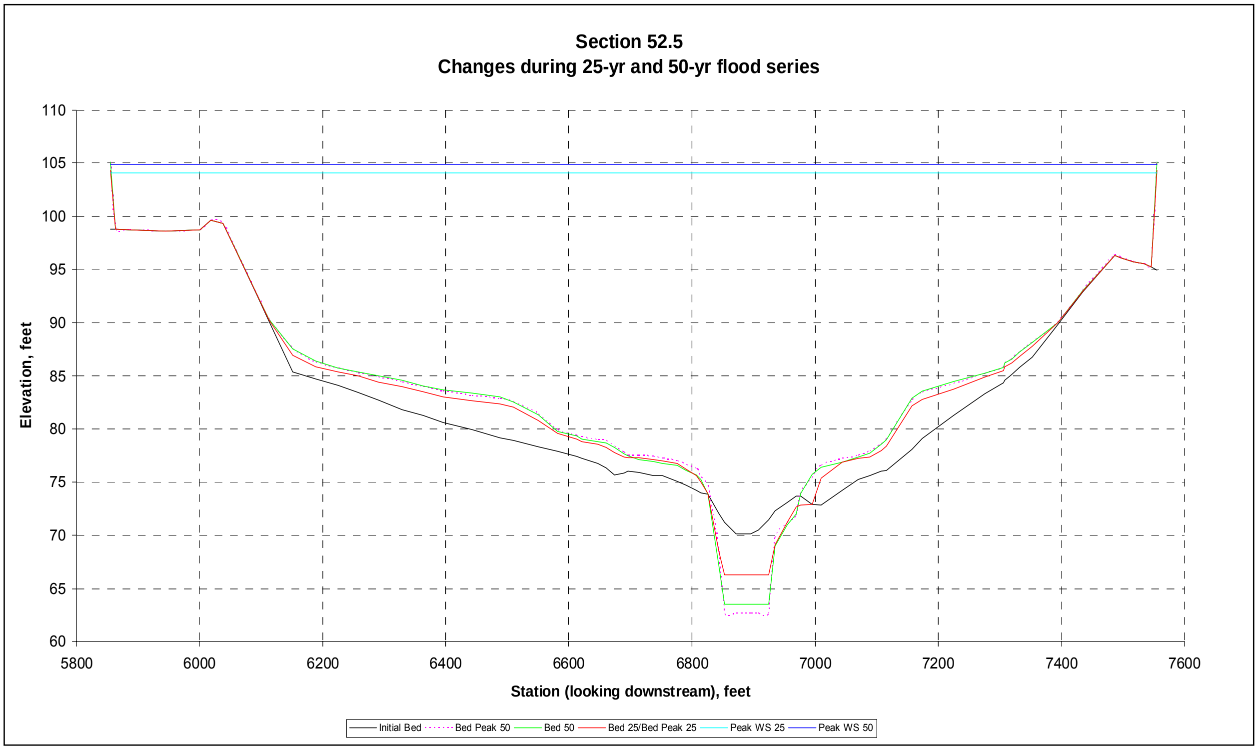
Section 51.3
Changes during 25-yr and 50-yr flood series
Elevation, feet
105
100
95
90
85
80
75
70
65
60
55
-100
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
2100
2200
2300
2400
2500
2600
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

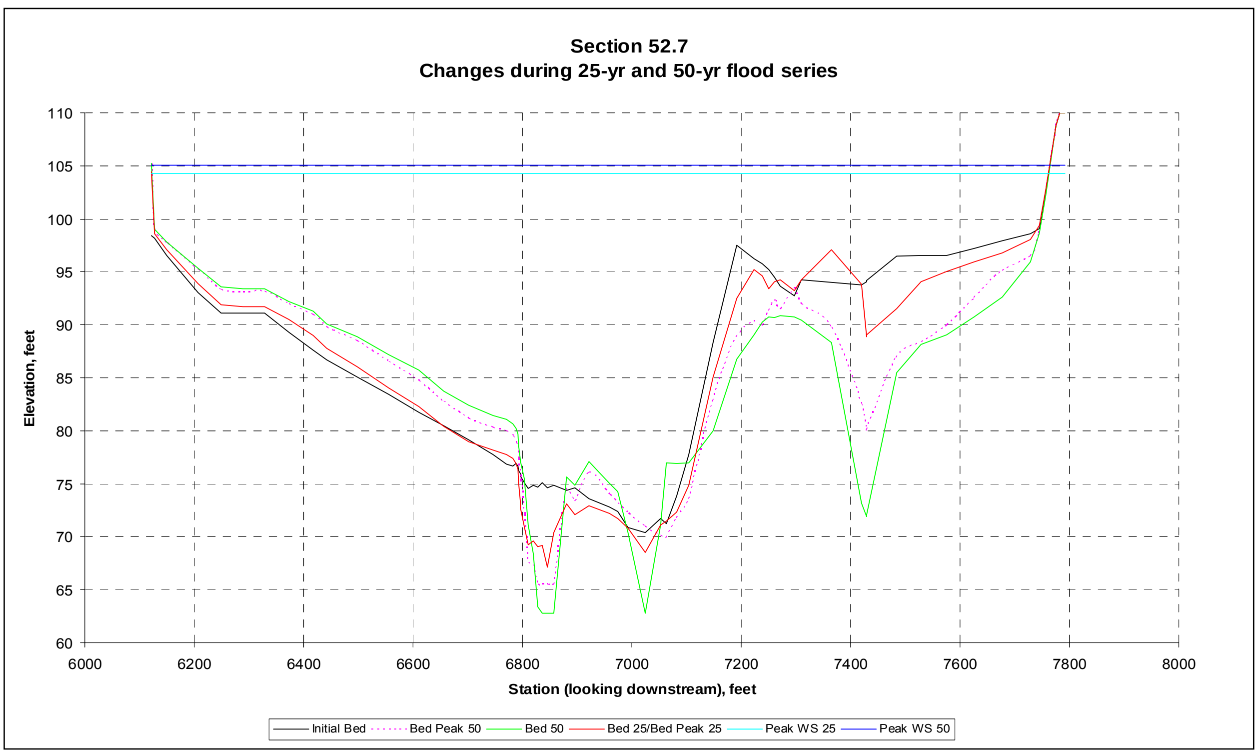

Section 51.4
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

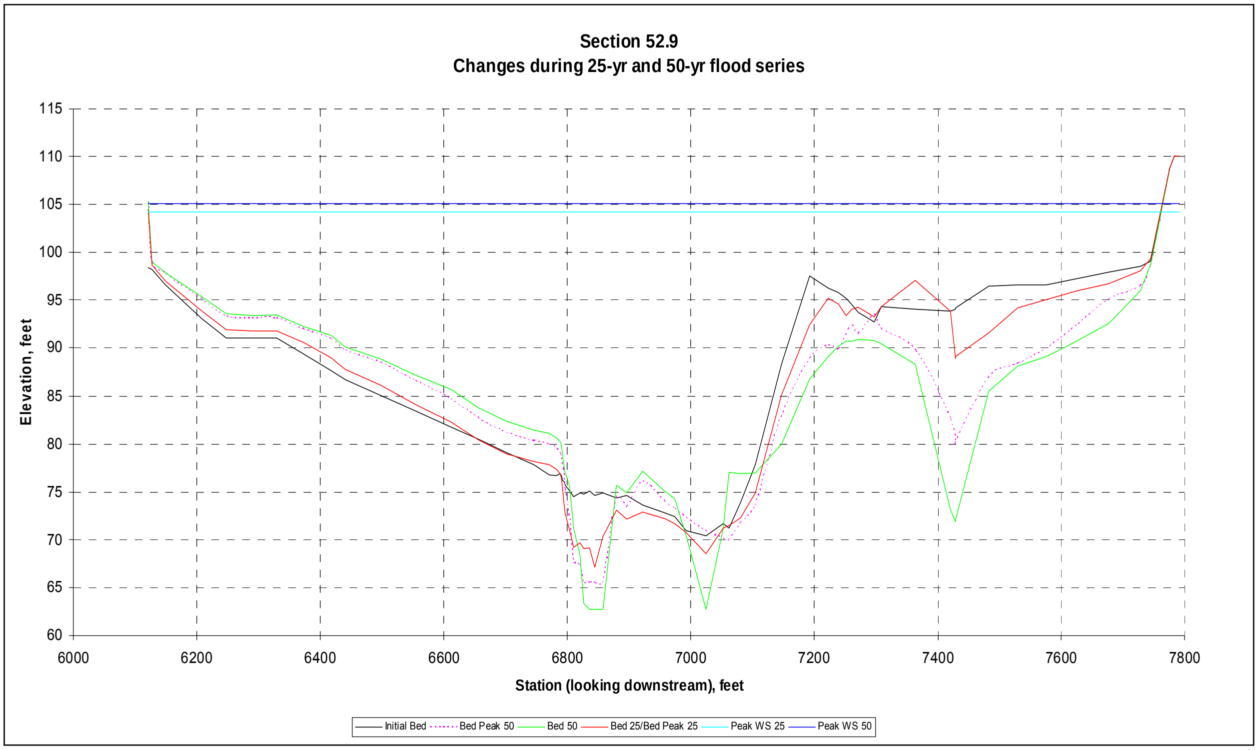

Section 51.7
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

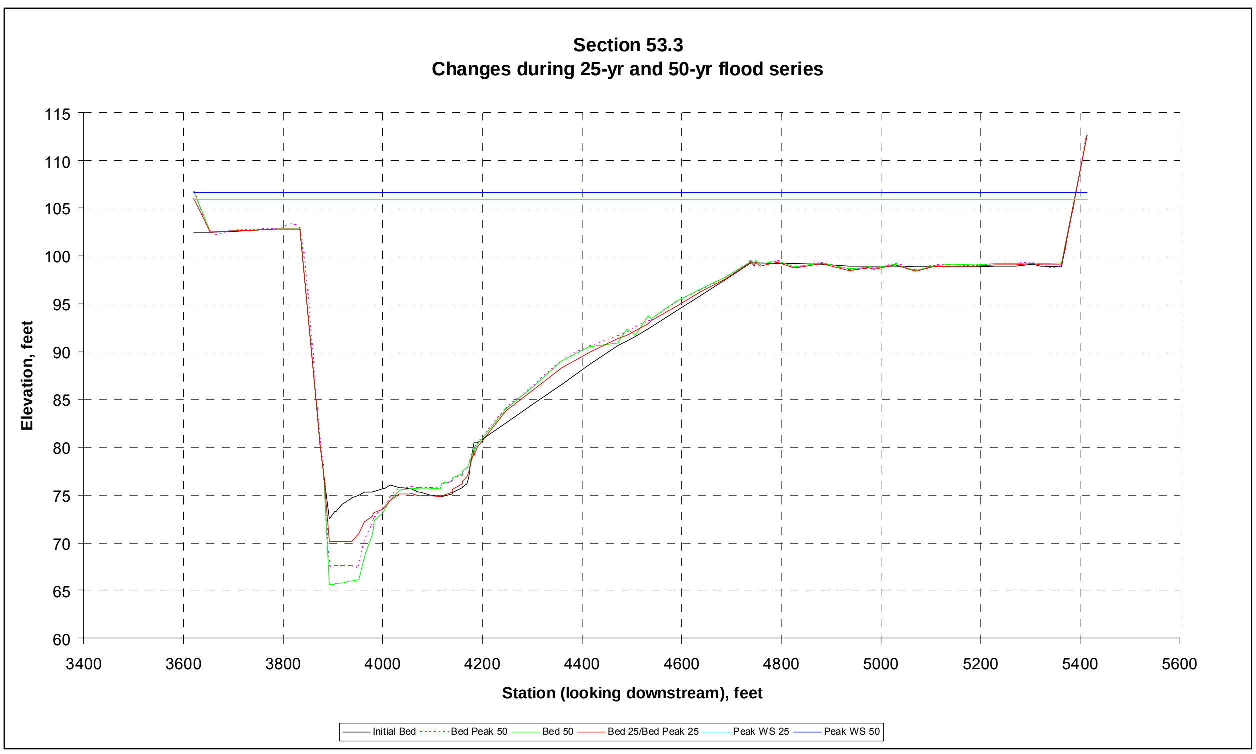

Section 51.9
Changes during 25-yr and 50-yr flood series
Elevation, feet
110
105
100
95
90
85
80
75
70
65
60
5700
5900
6100
6300
6500
6700
6900
7100
7300
7500
7700
7900
8100
8300
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

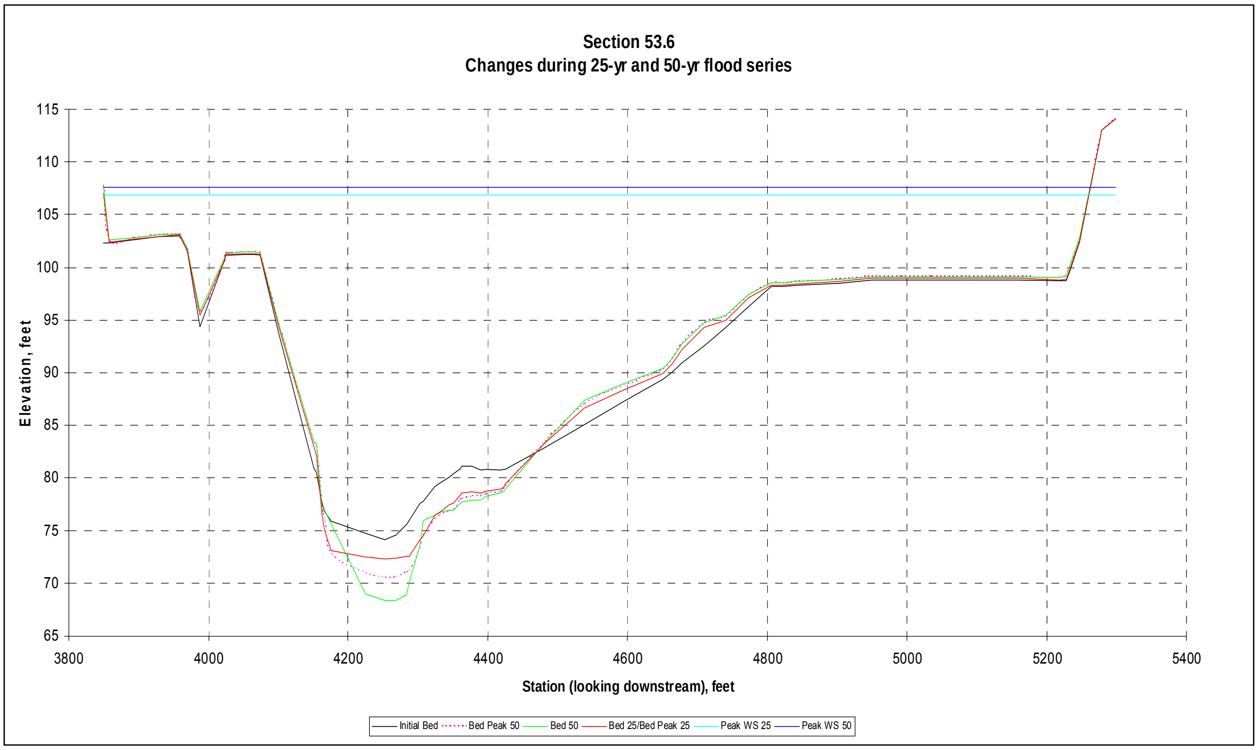

Section 52.3
Changes during 25-yr and 50-yr flood series
Elevation, feet
110
105
100
95
90
85
80
75
70
65
60
5700
5900
6100
6300
6500
6700
6900
7100
7300
7500
7700
7900
8100
8300
8500
8700
8900
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50


Section 52.5
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

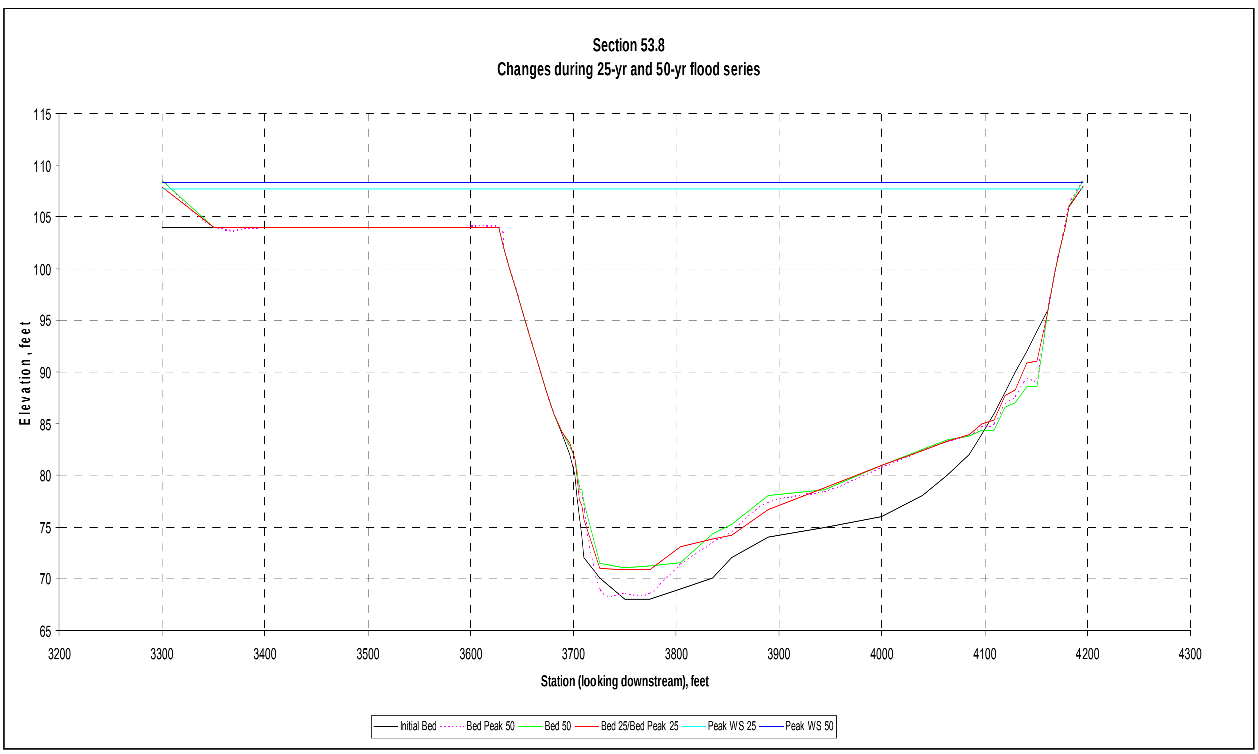

Section 52.7
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50


Section 52.9
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
115
110
105
100
95
90
85
80
75
70
65
60
6000
6200
6400
6600
6800
7000
7200
7400
7600
7800
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

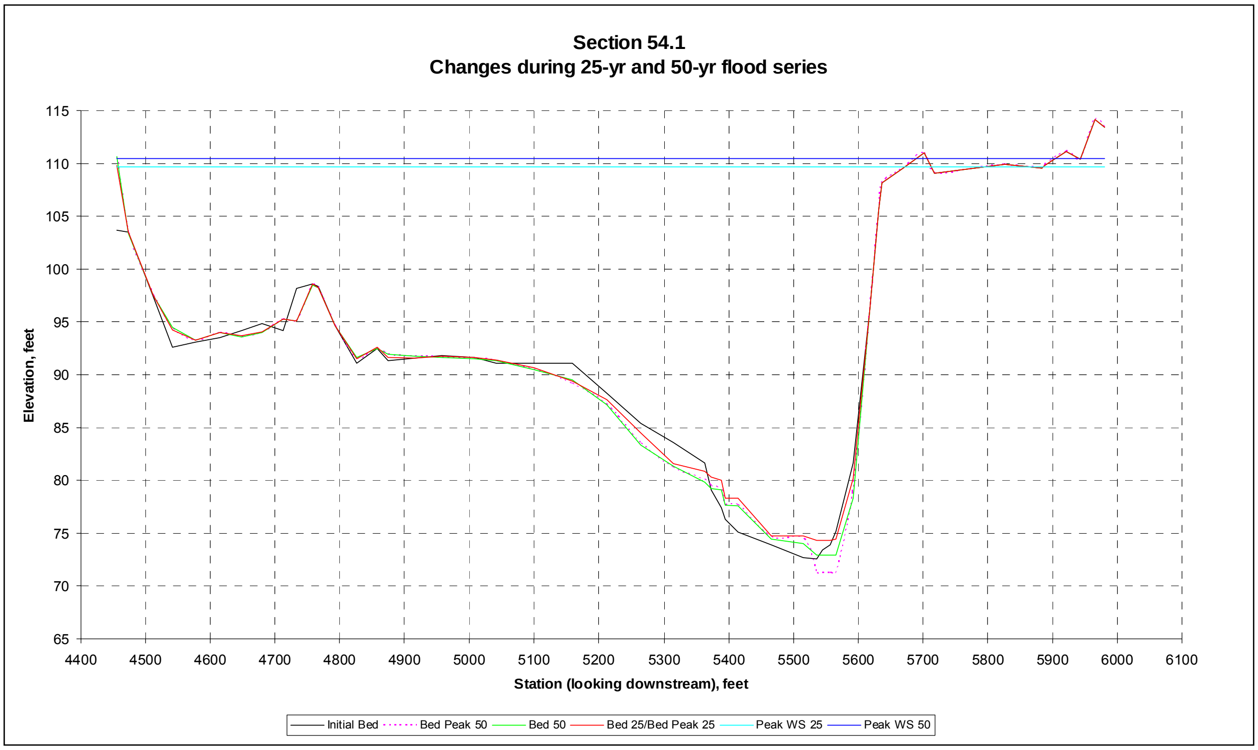

Section 53.3
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
115
110
105
100
95
90
85
80
75
70
65
60
3400
3600
3800
4000
4200
4400
4600
4800
5000
5200
5400
5600
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

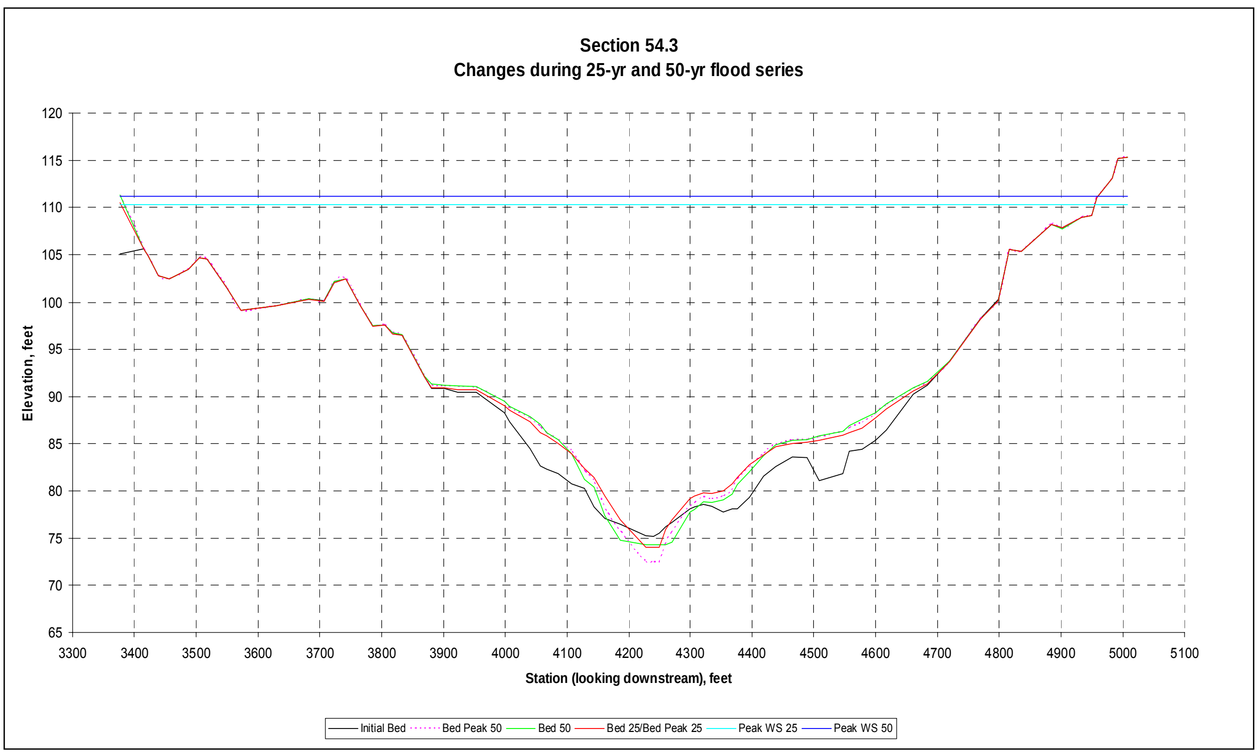


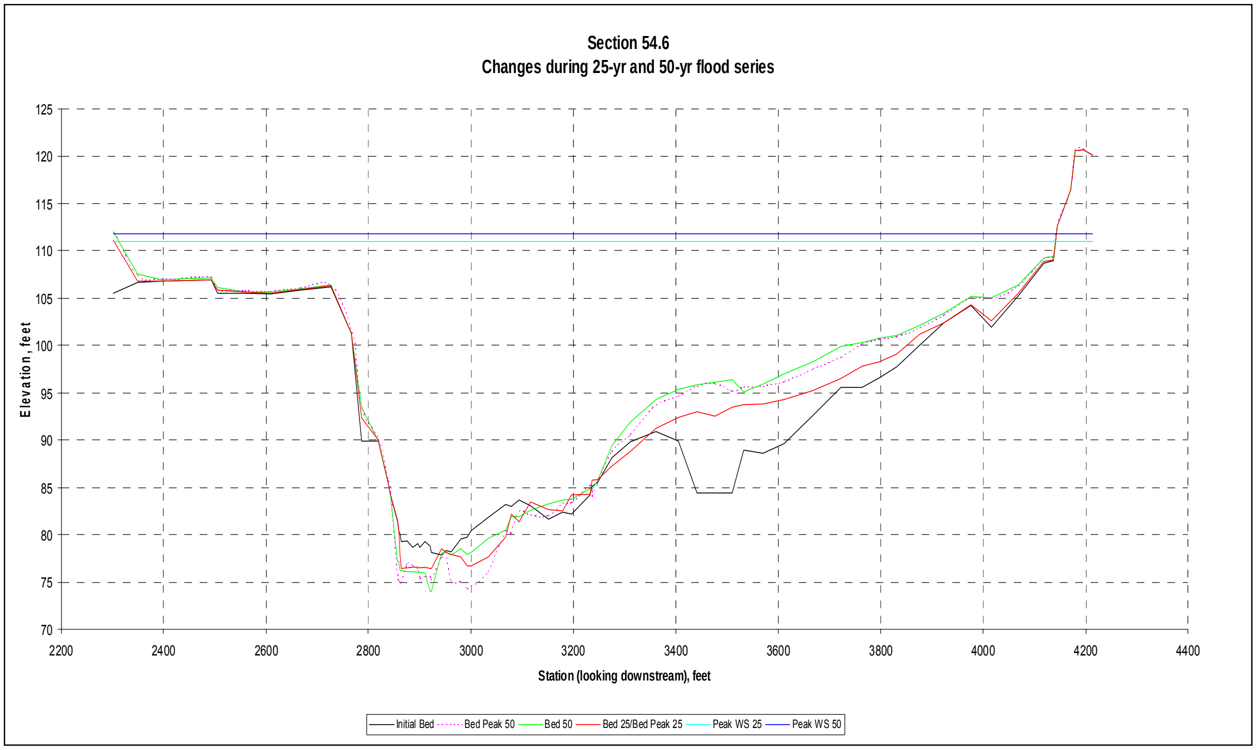
Section 53.6
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
115
110
105
100
95
90
85
80
75
70
65
3800
4000
4200
4400
4600
4800
5000
5200
5400
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50



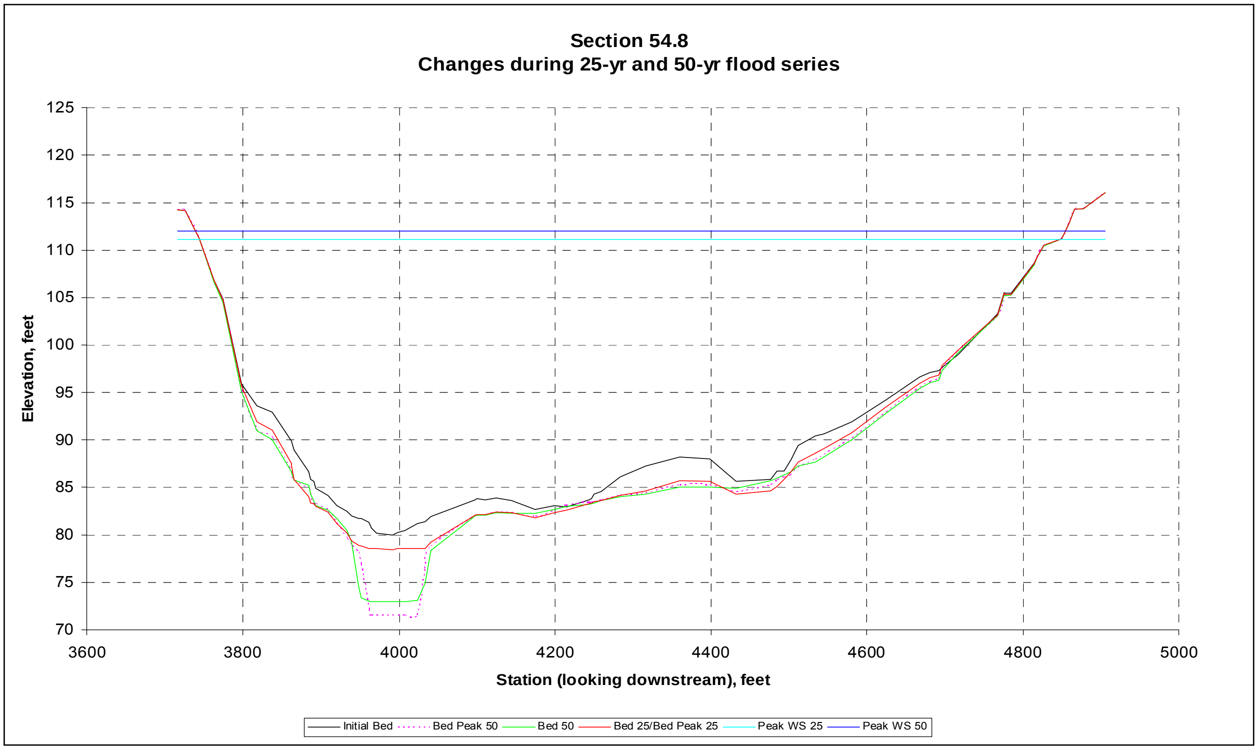
Section 53.8
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
115
110
105
100
95
90
85
80
75
70
65
3200
3300
3400
3500
3600
3700
3800
3900
4000
4100
4200
4300
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50


Section 54.1
Changes during 25-yr and 50-yr flood series
Elevation, feet
115
110
105
100
95
90
85
80
75
70
65
4400
4500
4600
4700
4800
4900
5000
5100
5200
5300
5400
5500
5600
5700
5800
5900
6000
6100
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

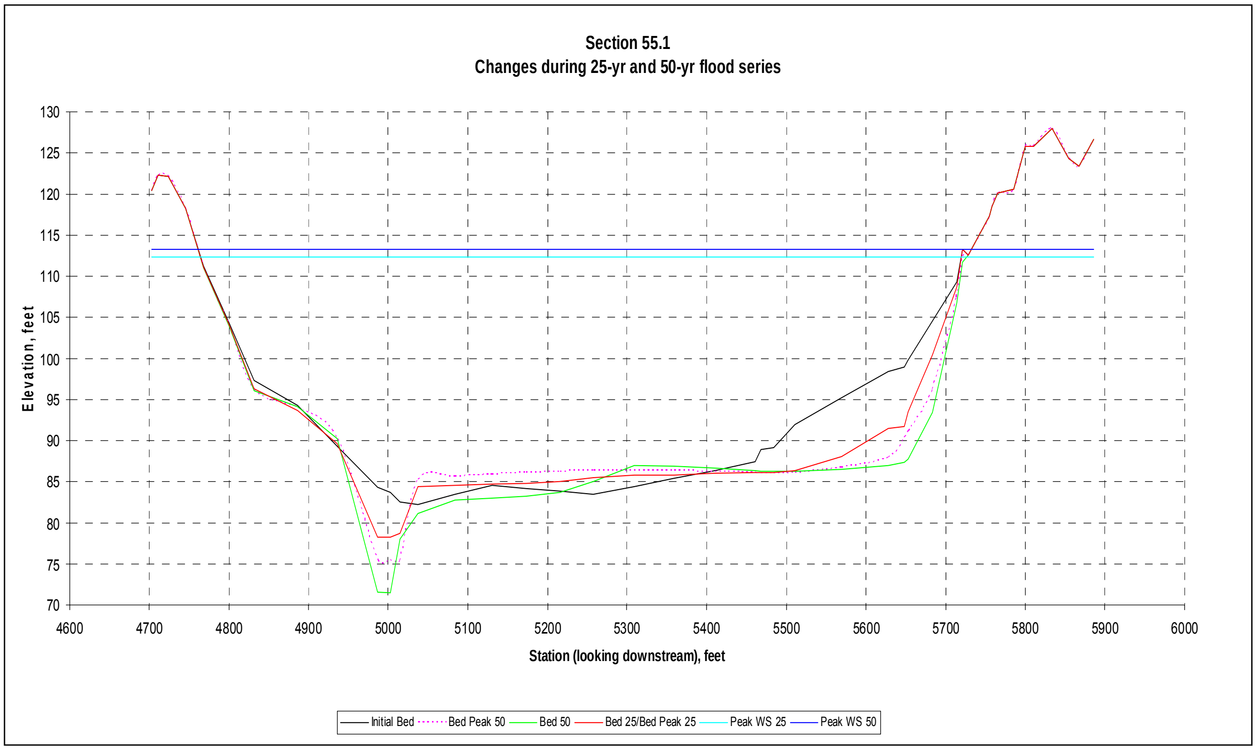

Section 54.3
Changes during 25-yr and 50-yr flood series
Elevation, feet
120
115
110
105
100
95
90
85
80
75
70
65
3300
3400
3500
3600
3700
3800
3900
4000
4100
4200
4300
4400
4500
4600
4700
4800
4900
5000
5100
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

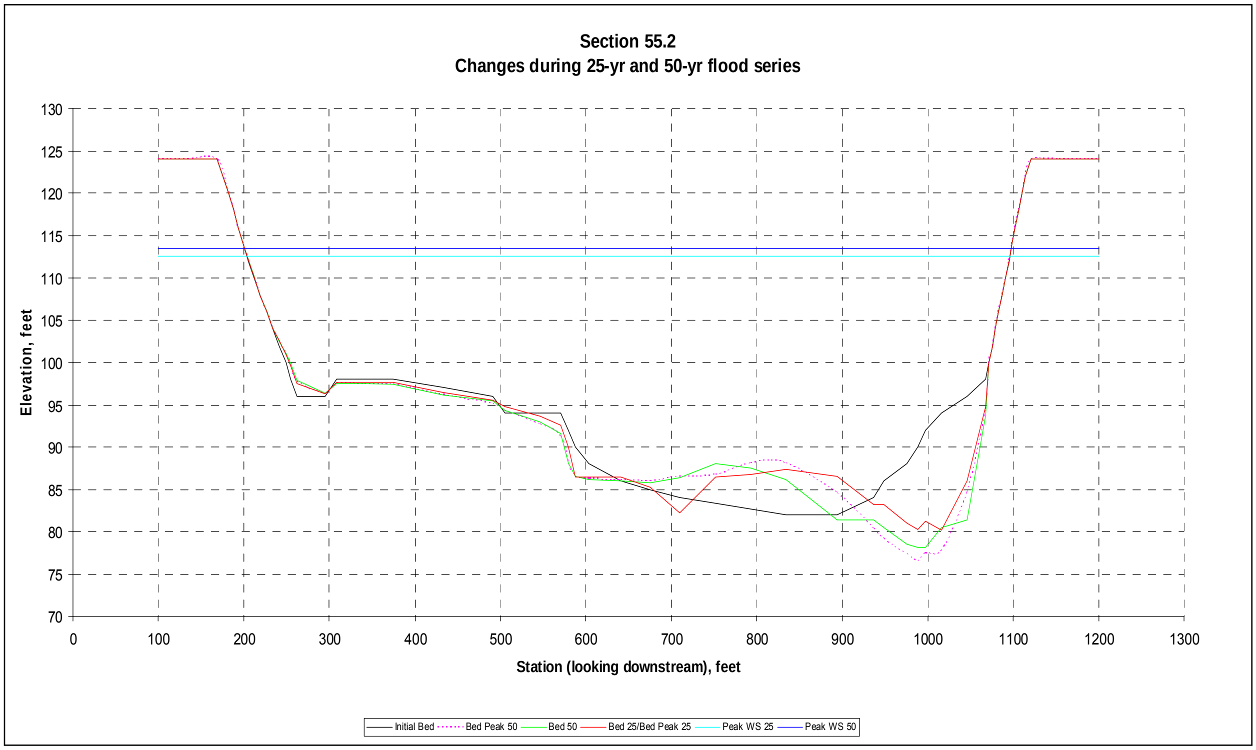


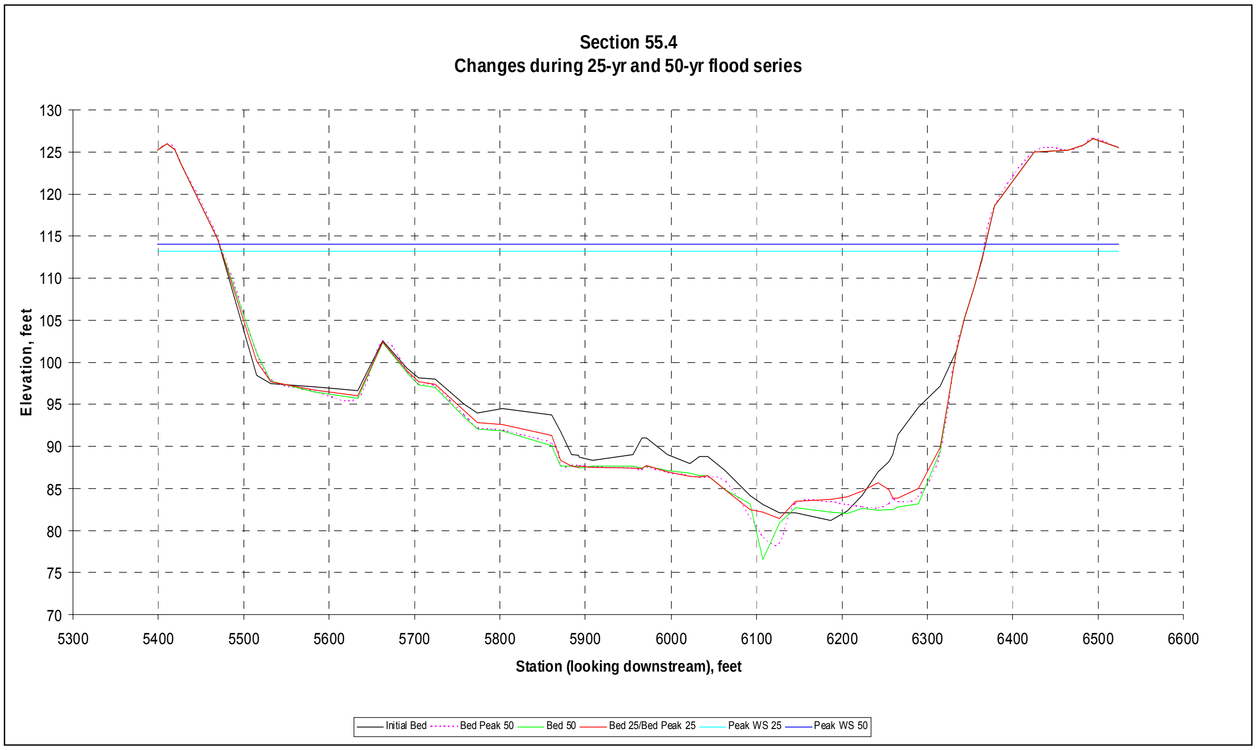
Section 54.6
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

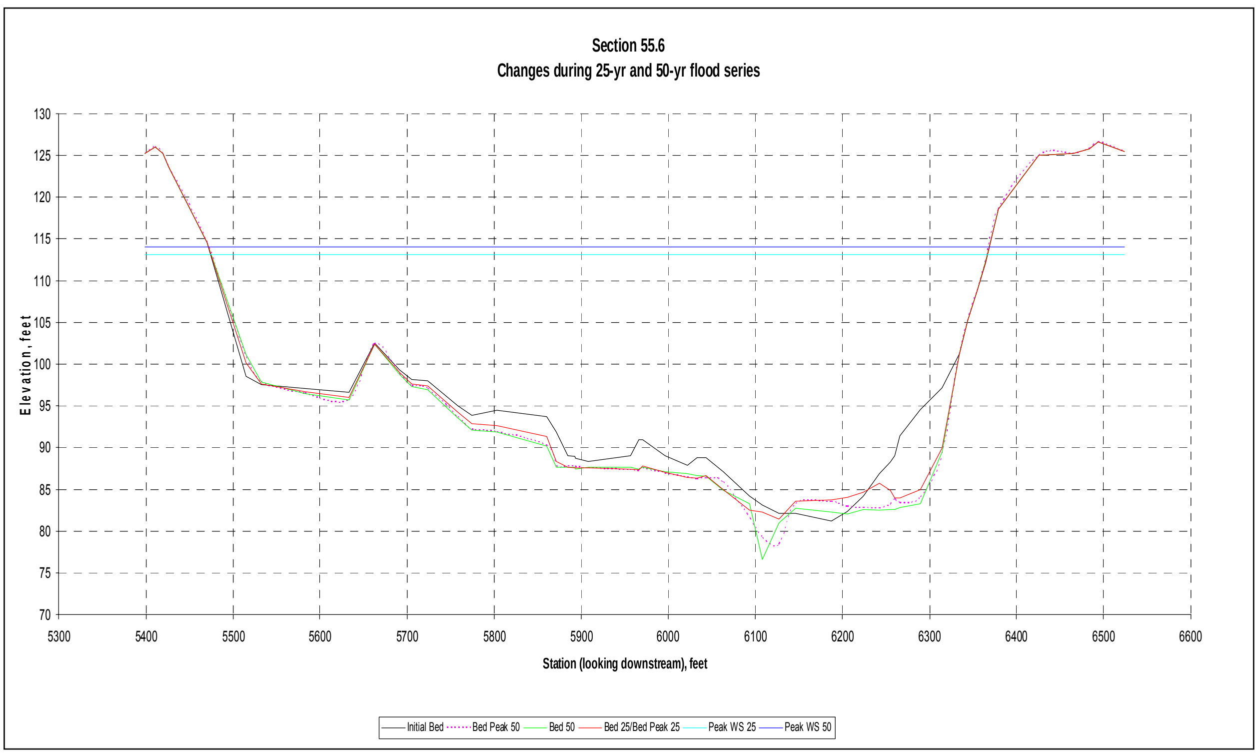


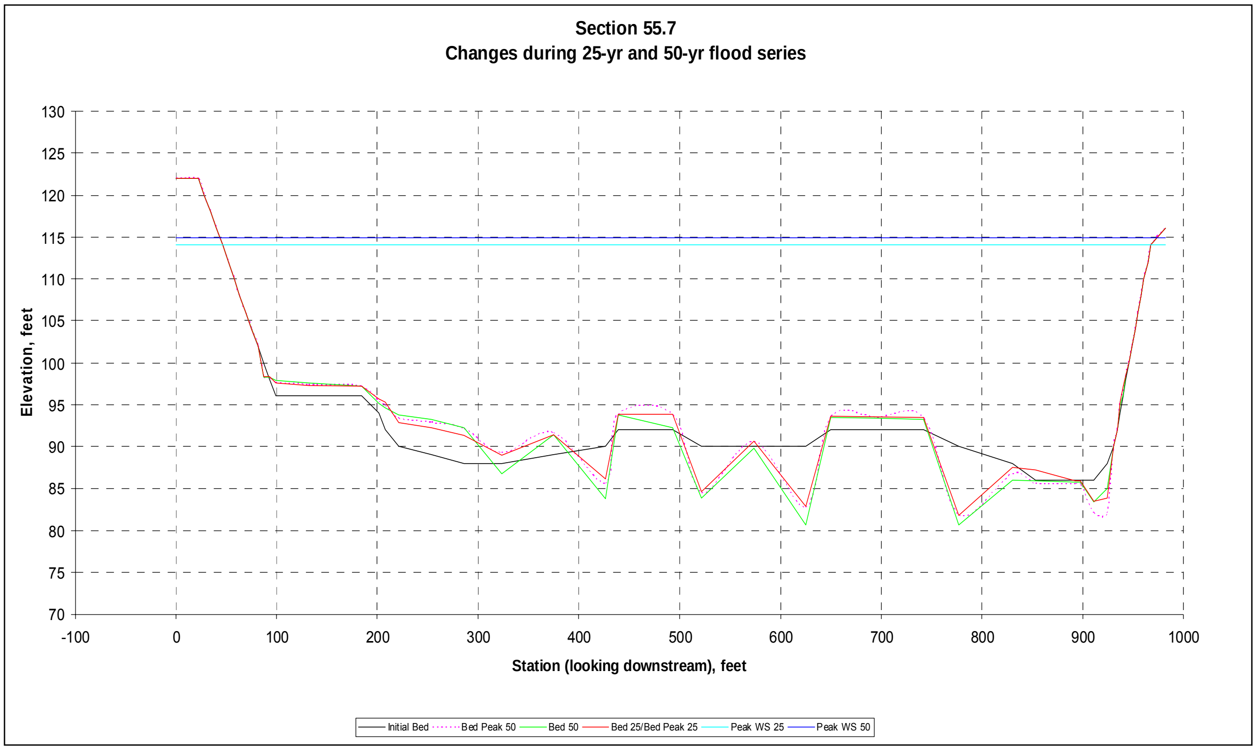
Section 54.8
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

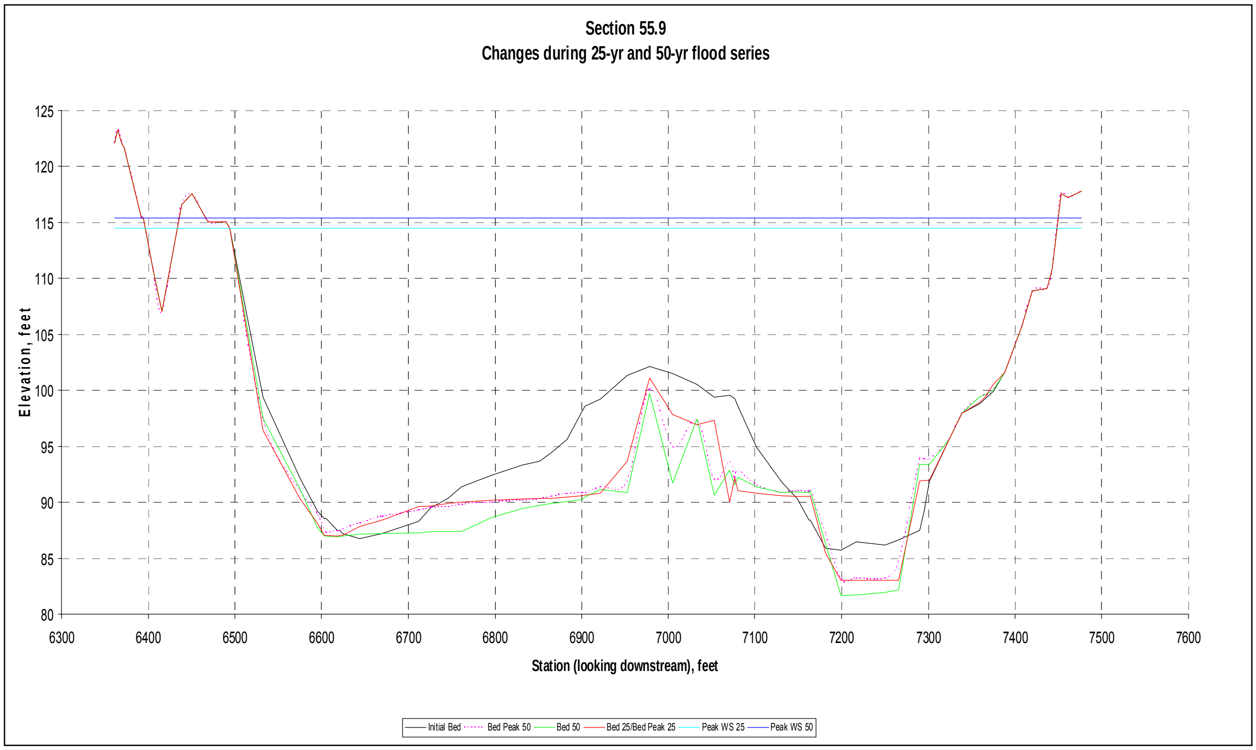

Section 55.1
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

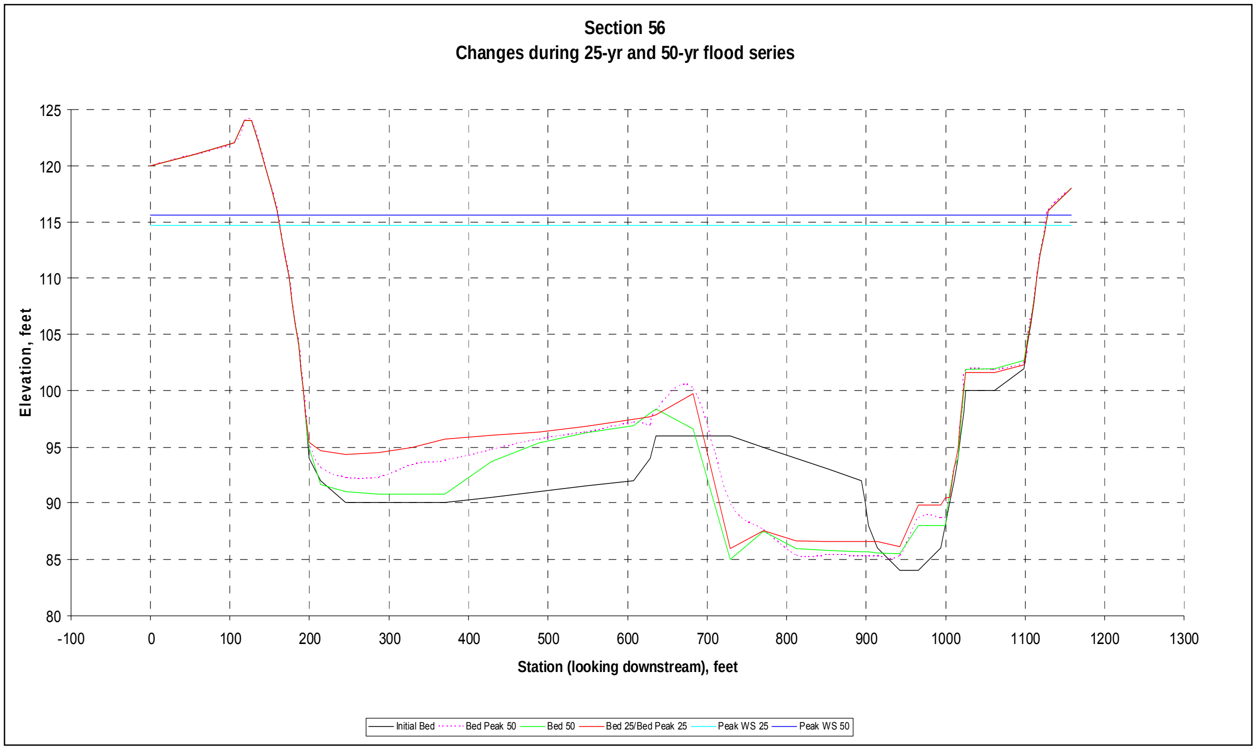

Section 55.2
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50


Section 55.4
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
130
125
120
115
110
105
100
95
90
85
80
75
70
5300
5400
5500
5600
5700
5800
5900
6000
6100
6200
6300
6400
6500
6600
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

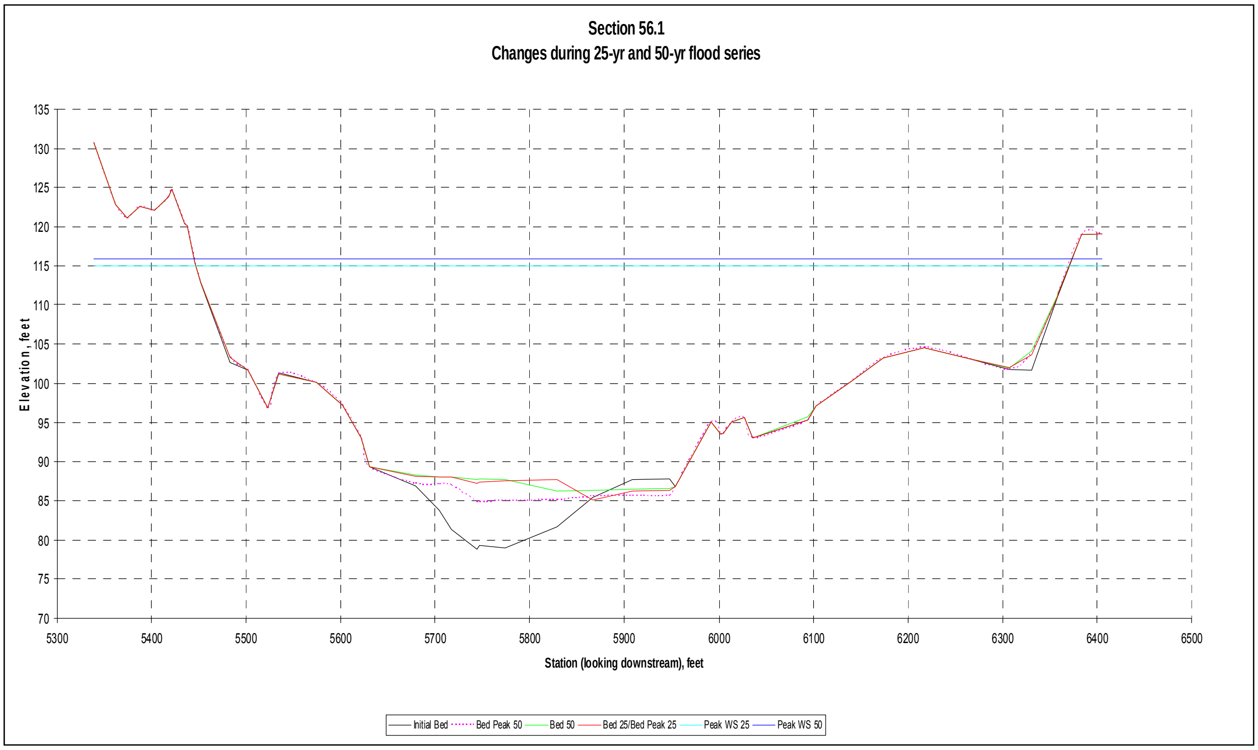

Section 55.6
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
130
125
120
115
110
105
100
95
90
85
80
75
70
5300
5400
5500
5600
5700
5800
5900
6000
6100
6200
6300
6400
6500
6600
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50


Section 55.7
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
130
125
120
115
110
105
100
95
90
85
80
75
70
-100
0
100
200
300
400
500
600
700
800
900
1000
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

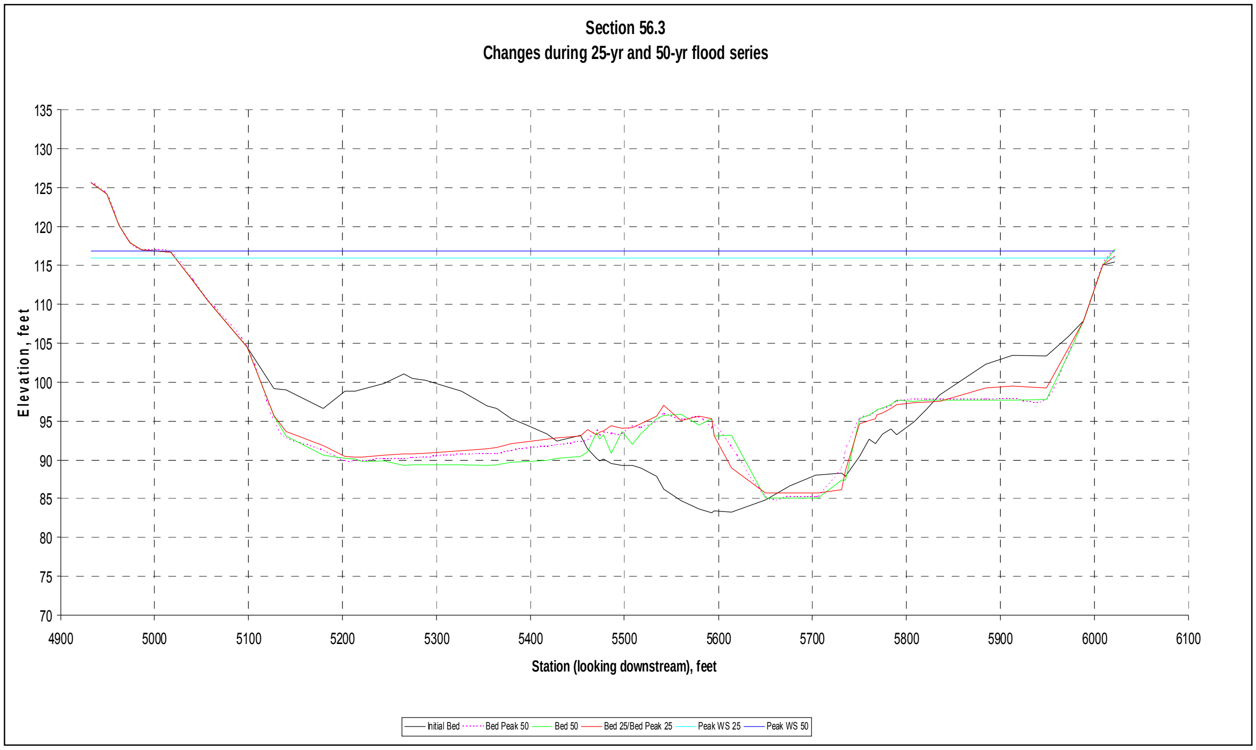

Section 55.9
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
125
120
115
110
105
100
95
90
85
80
6300
6400
6500
6600
6700
6800
6900
7000
7100
7200
7300
7400
7500
7600
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

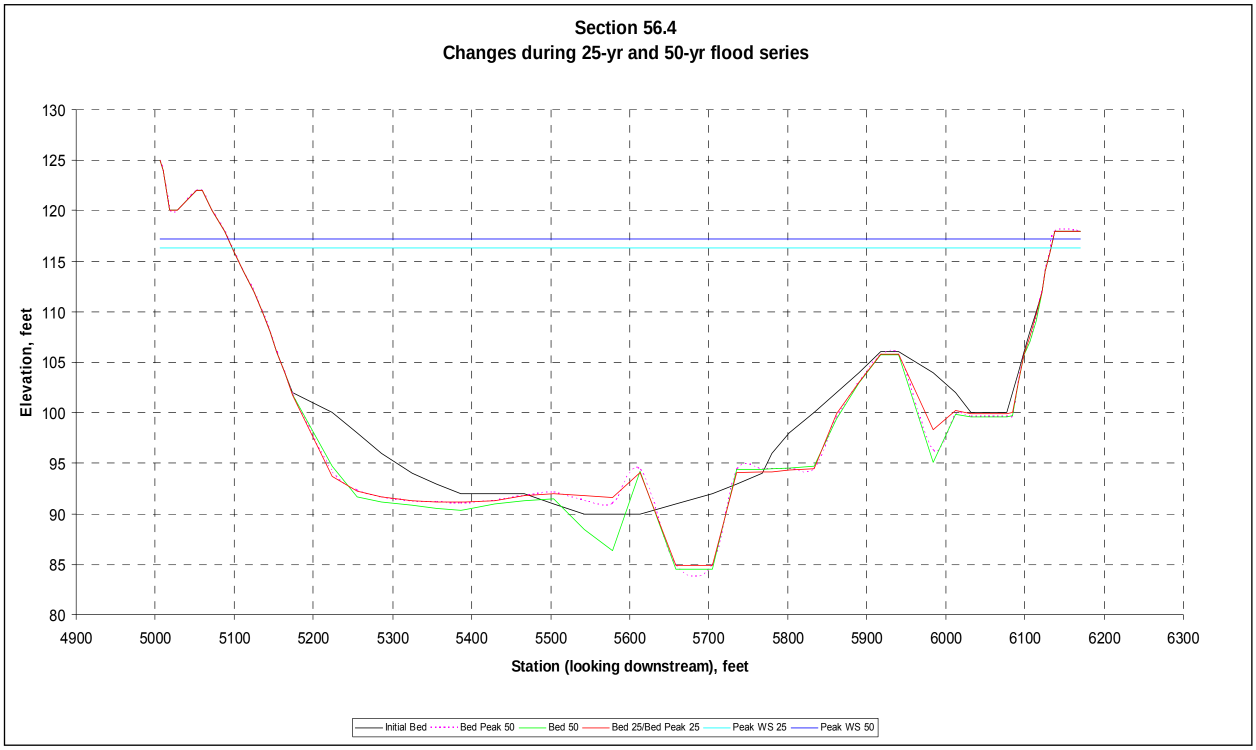


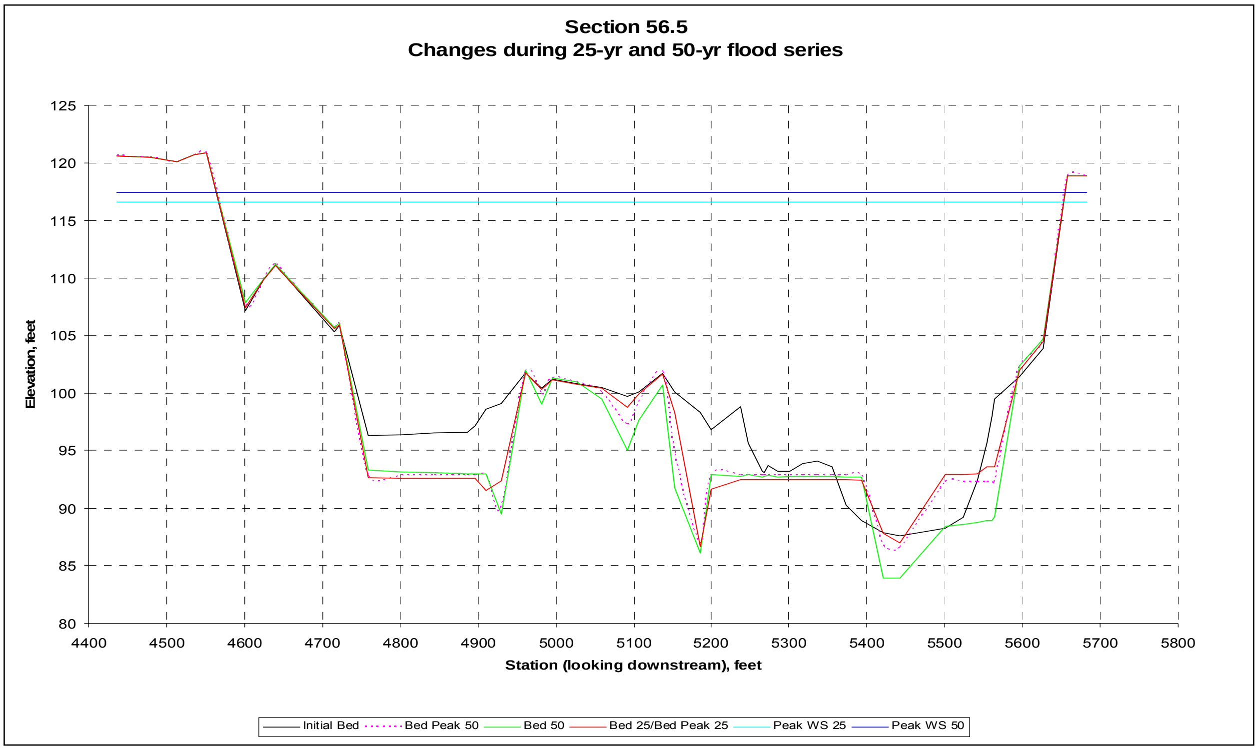
Section 56
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

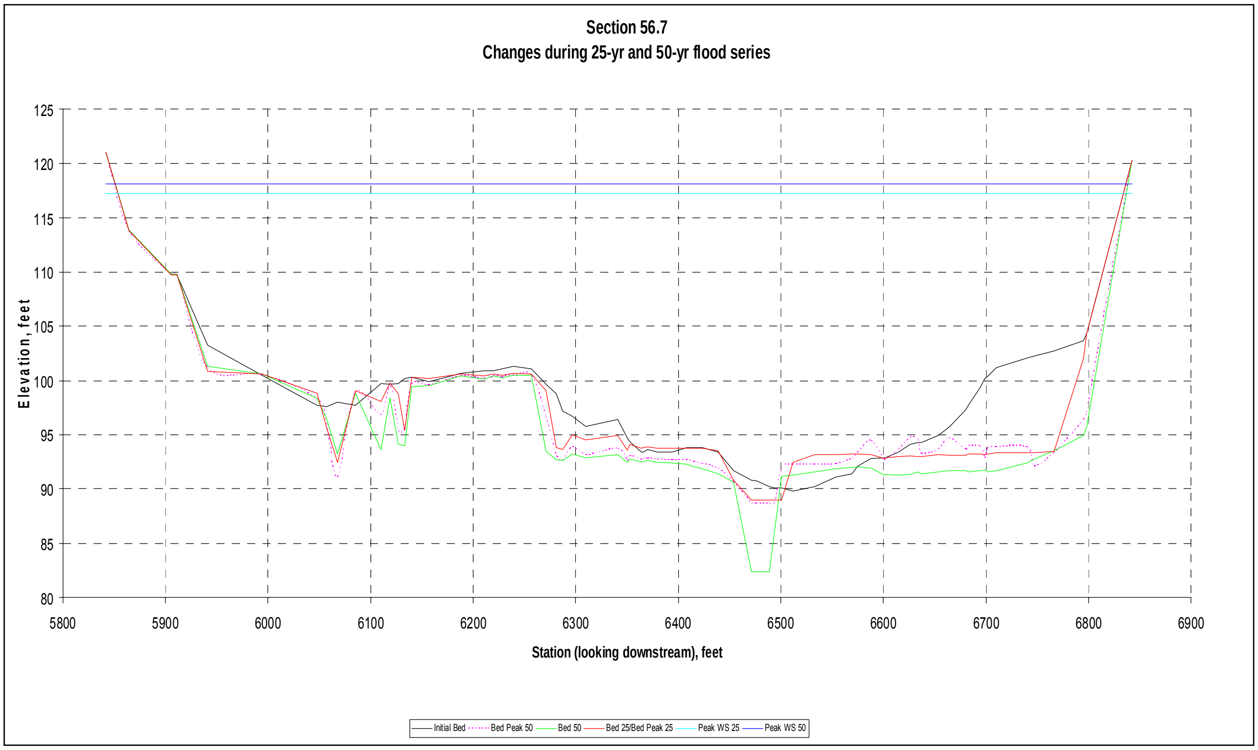


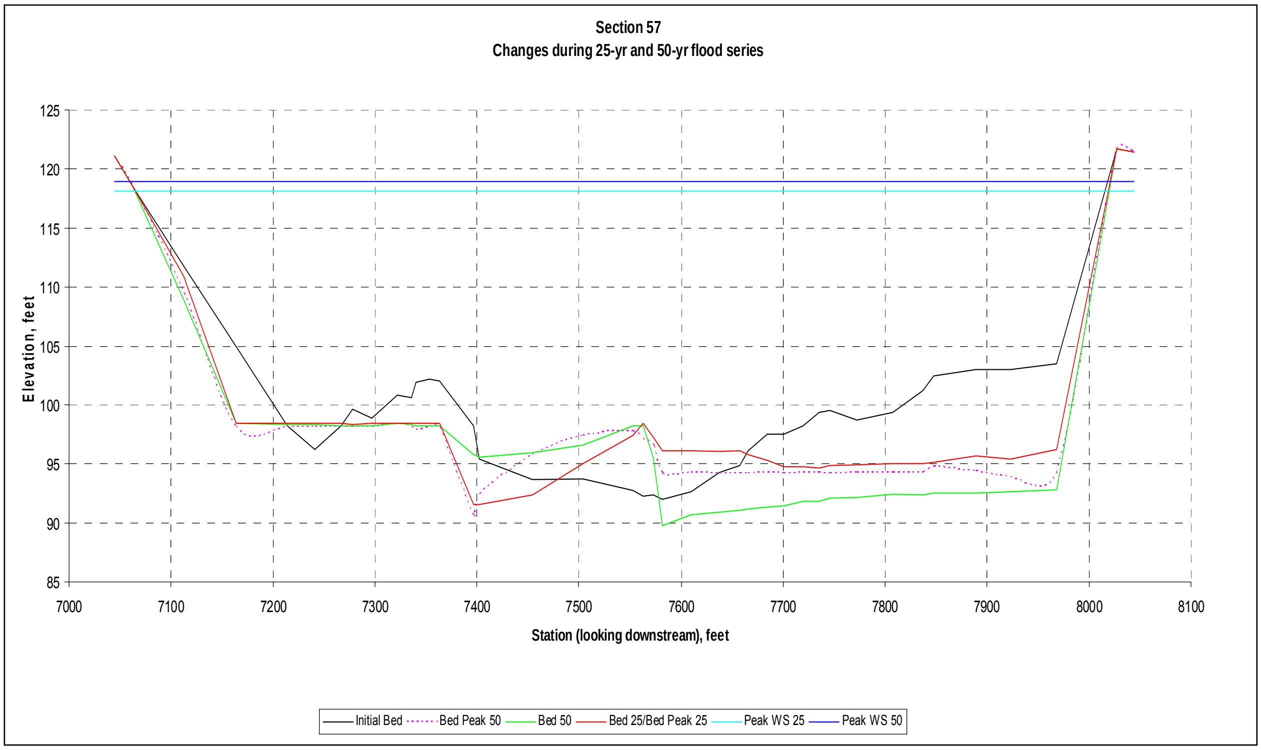
Section 56.1
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

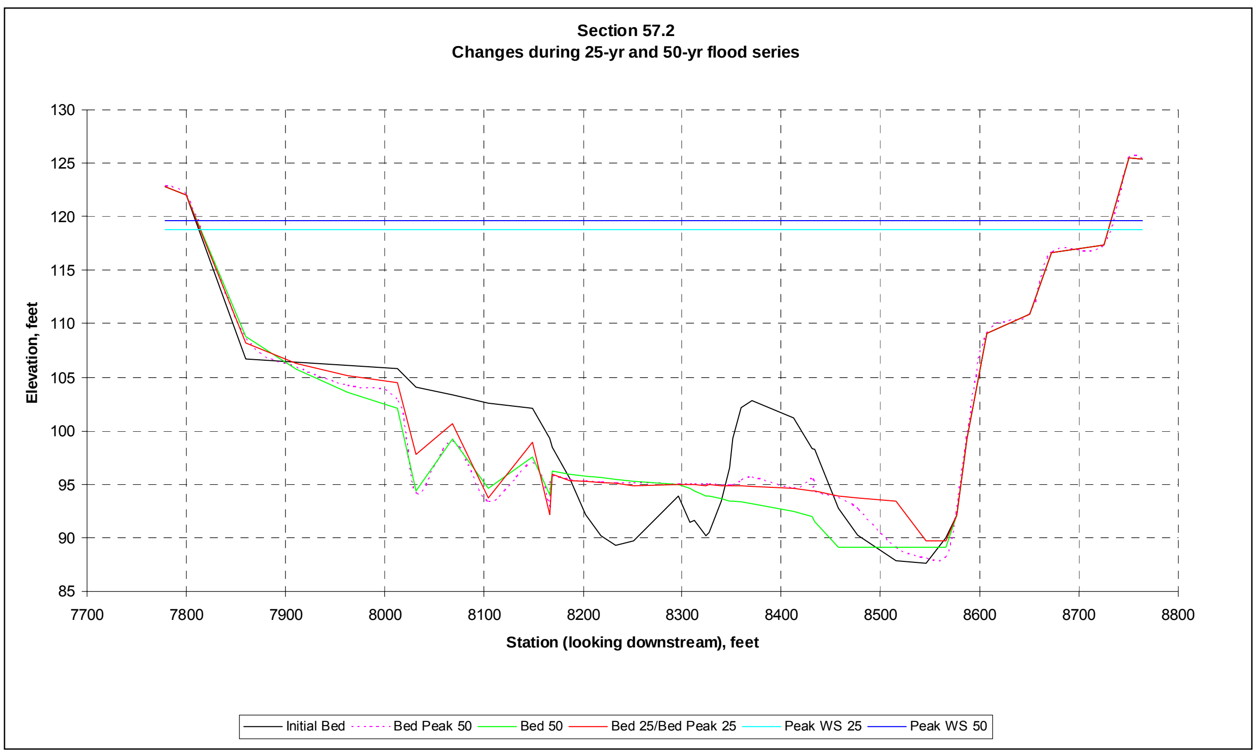

Section 56.3
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

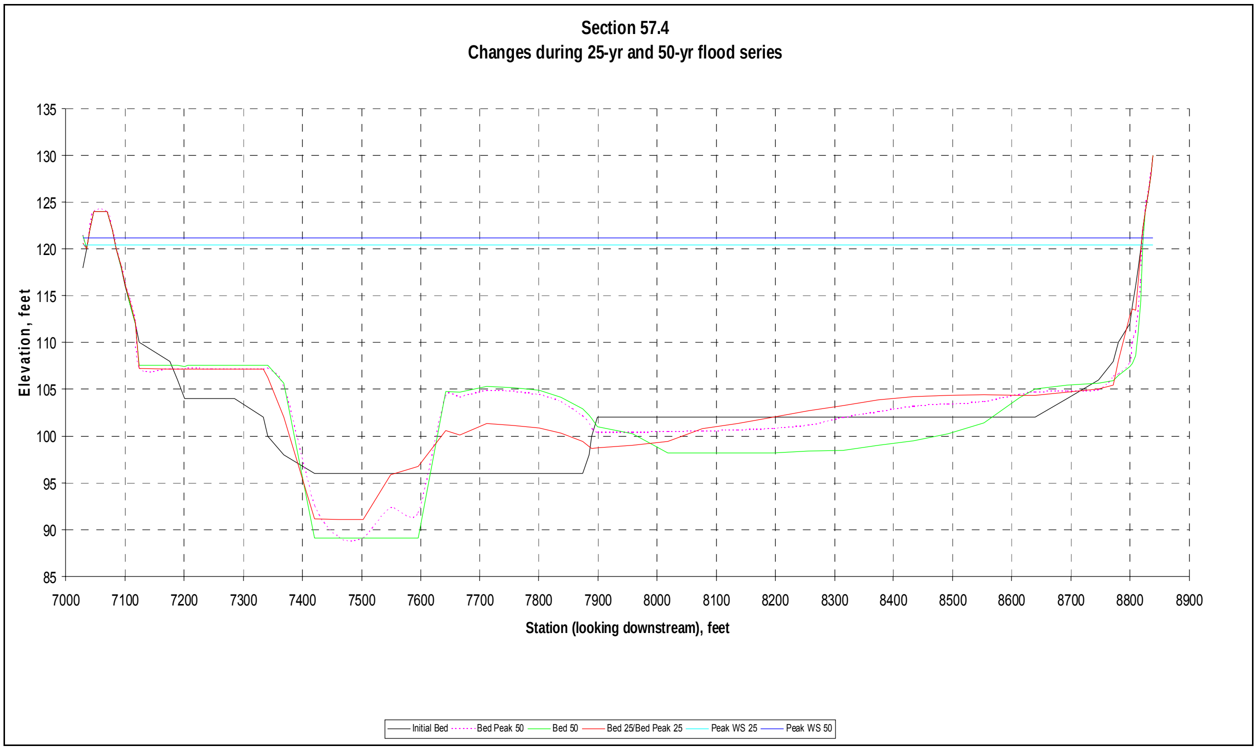

Section 56.4
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

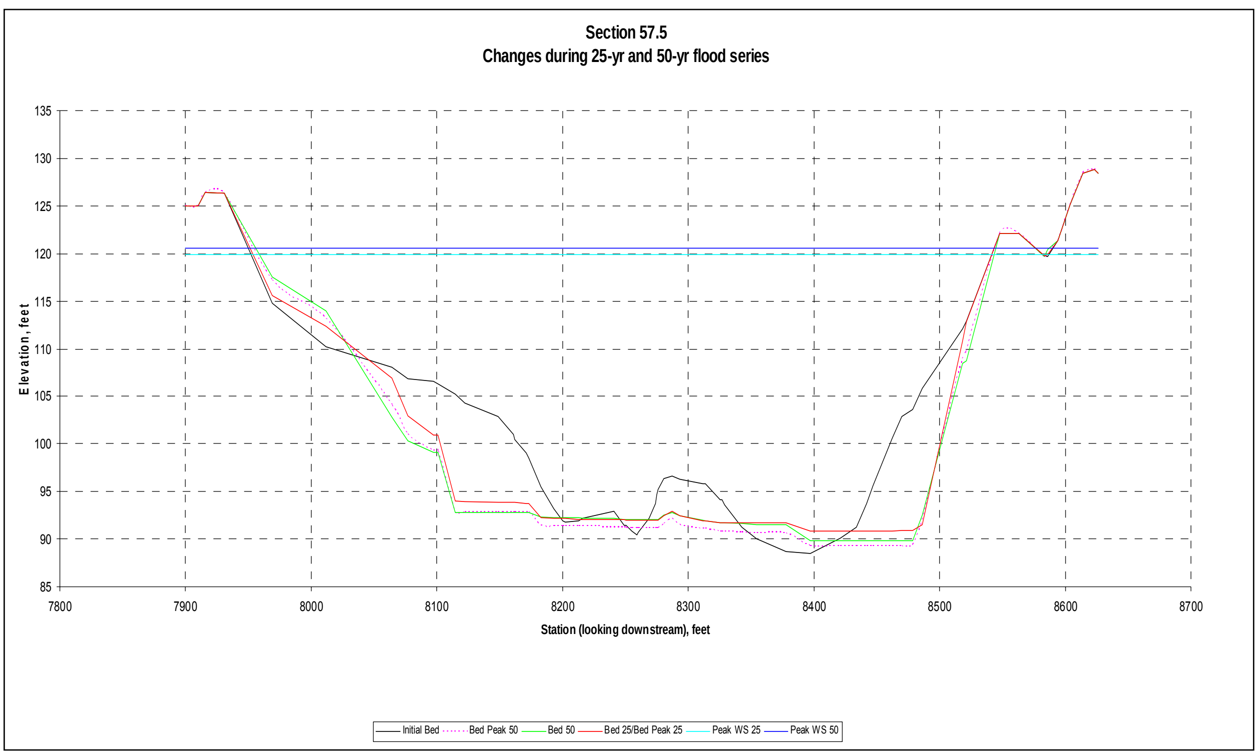

Section 56.5
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

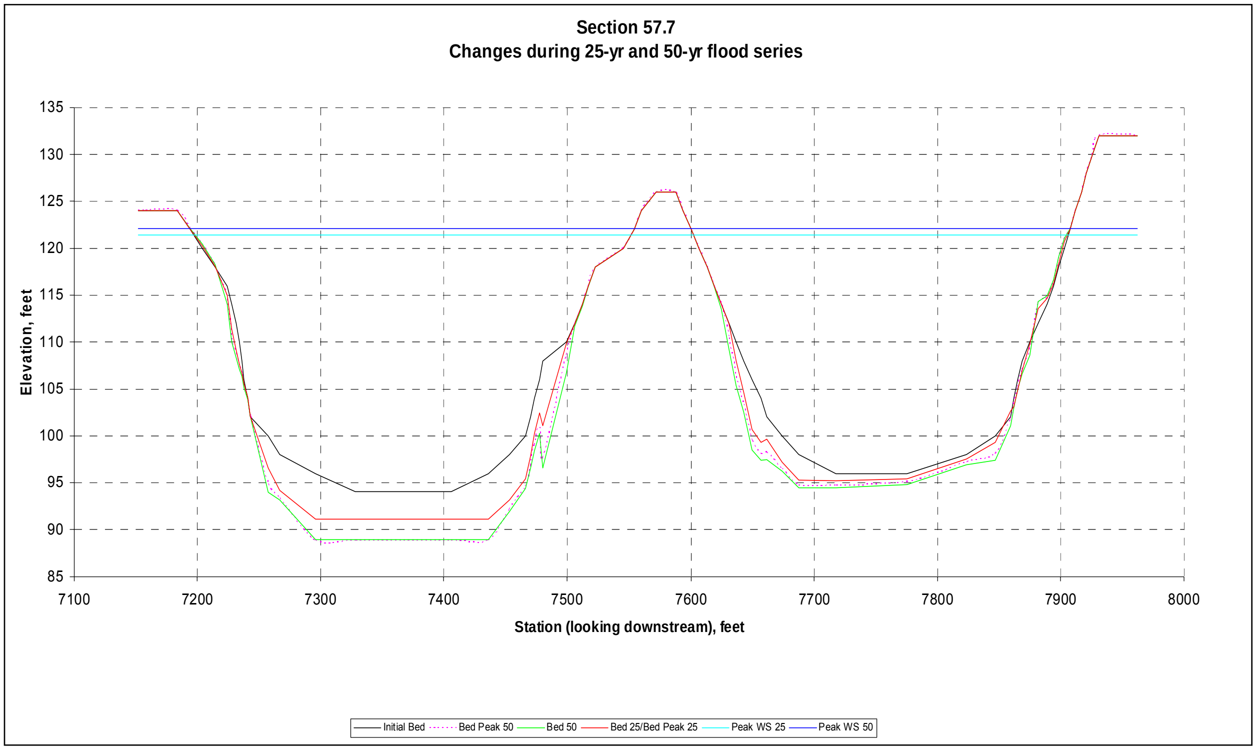

Section 56.7
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

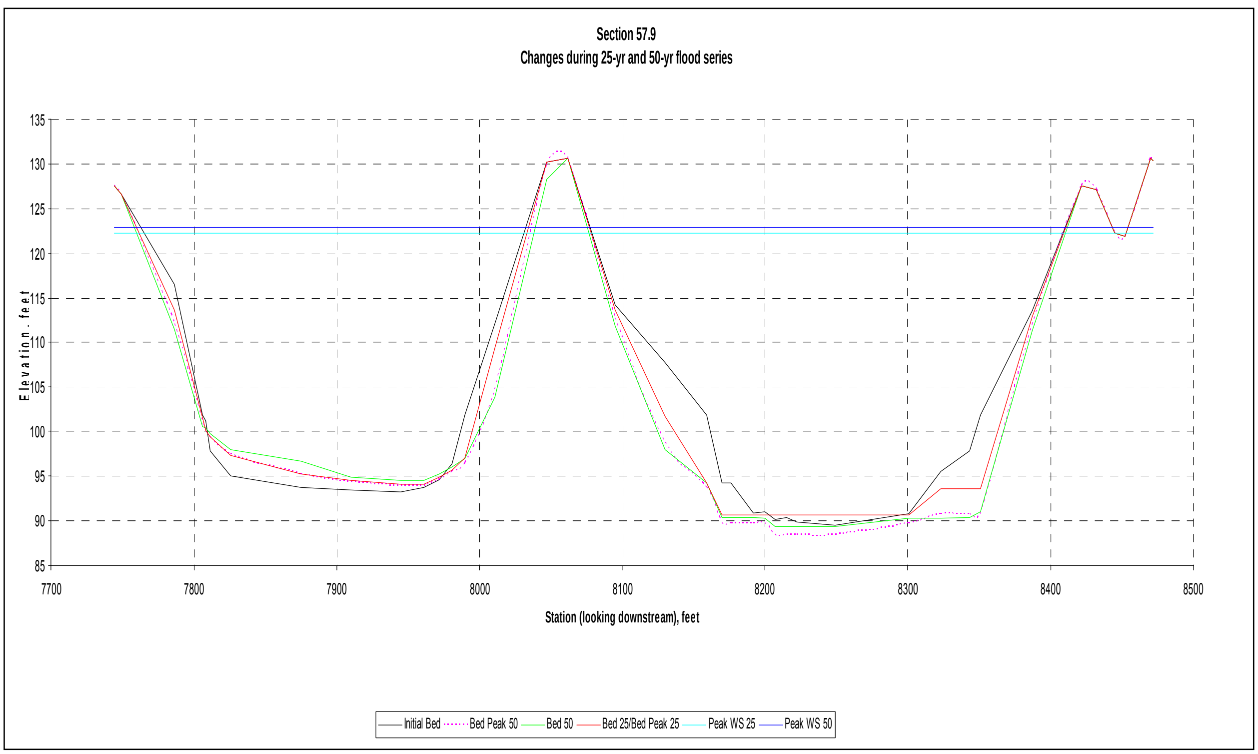

Section 57
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
125
120
115
110
105
100
95
90
85
7000
7100
7200
7300
7400
7500
7600
7700
7800
7900
8000
8100
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

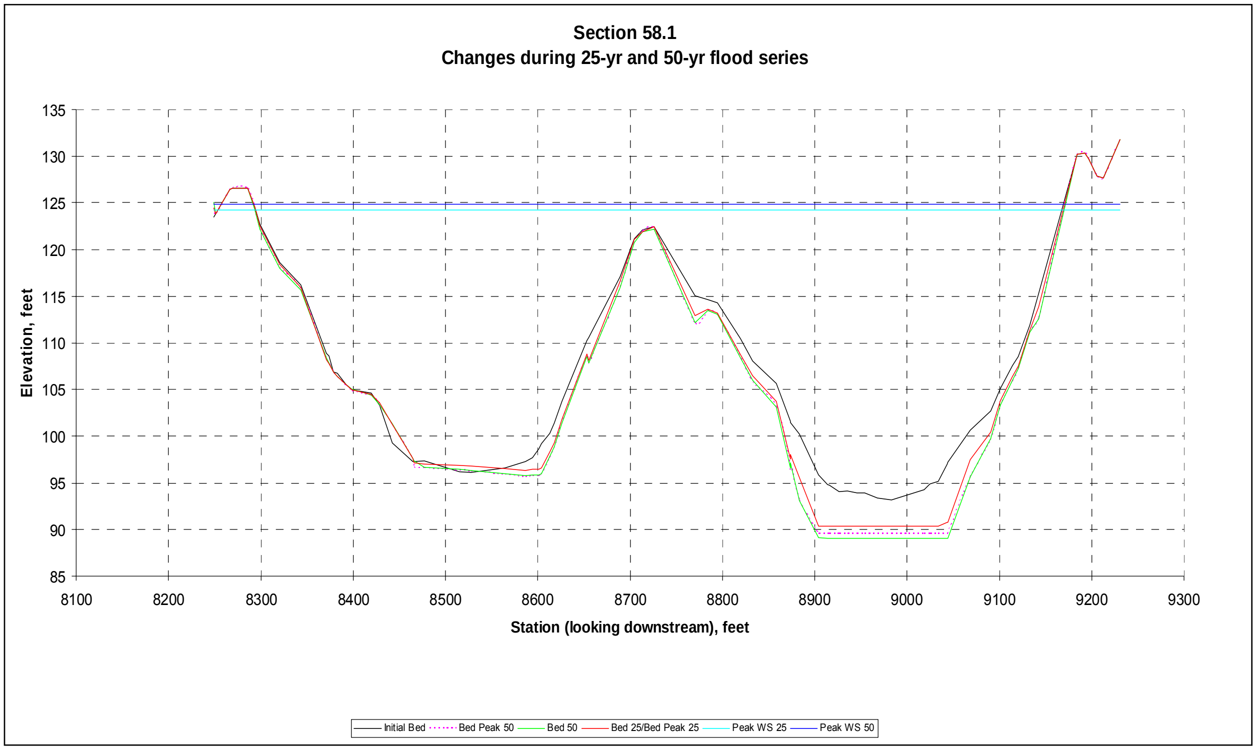

Section 57.2
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
130
125
120
115
110
105
100
95
90
85
7700
7800
7900
8000
8100
8200
8300
8400
8500
8600
8700
8800
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

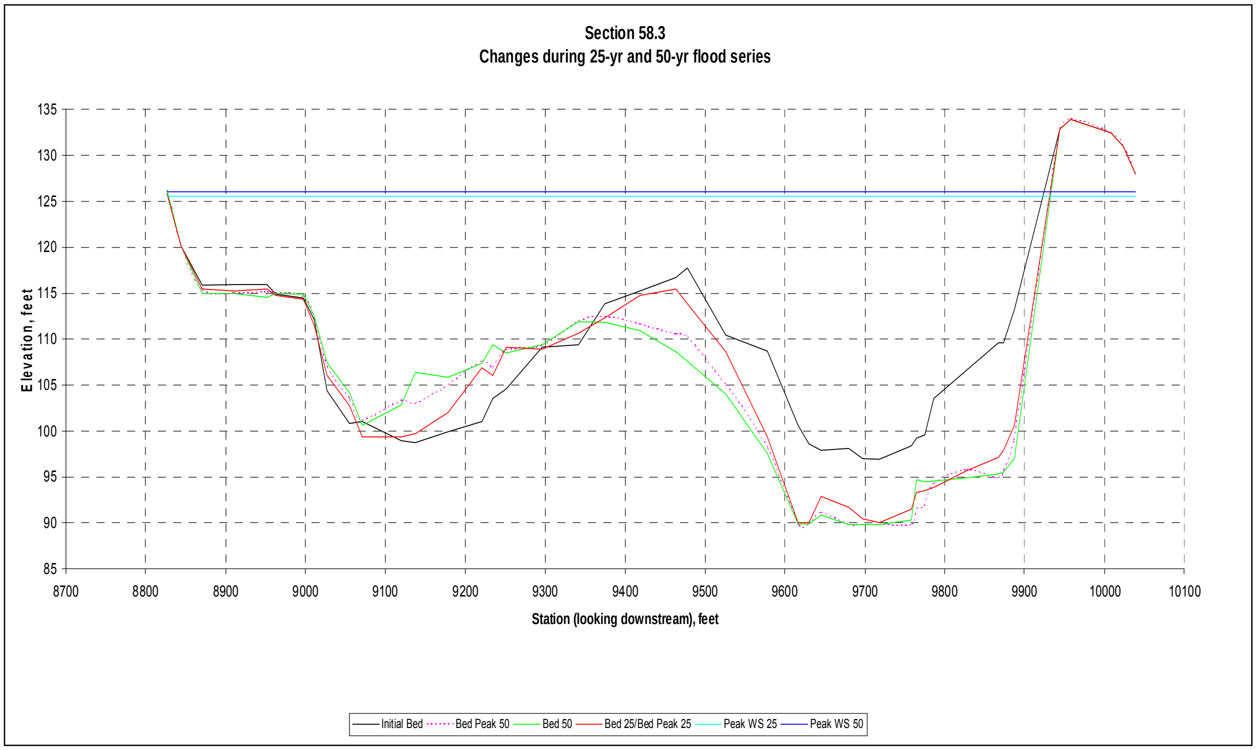

Section 57.4
Changes during 25-yr and 50-yr flood series
Elevation, feet
135
130
125
120
115
110
105
100
95
90
85
7000
7100
7200
7300
7400
7500
7600
7700
7800
7900
8000
8100
8200
8300
8400
8500
8600
8700
8800
8900
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

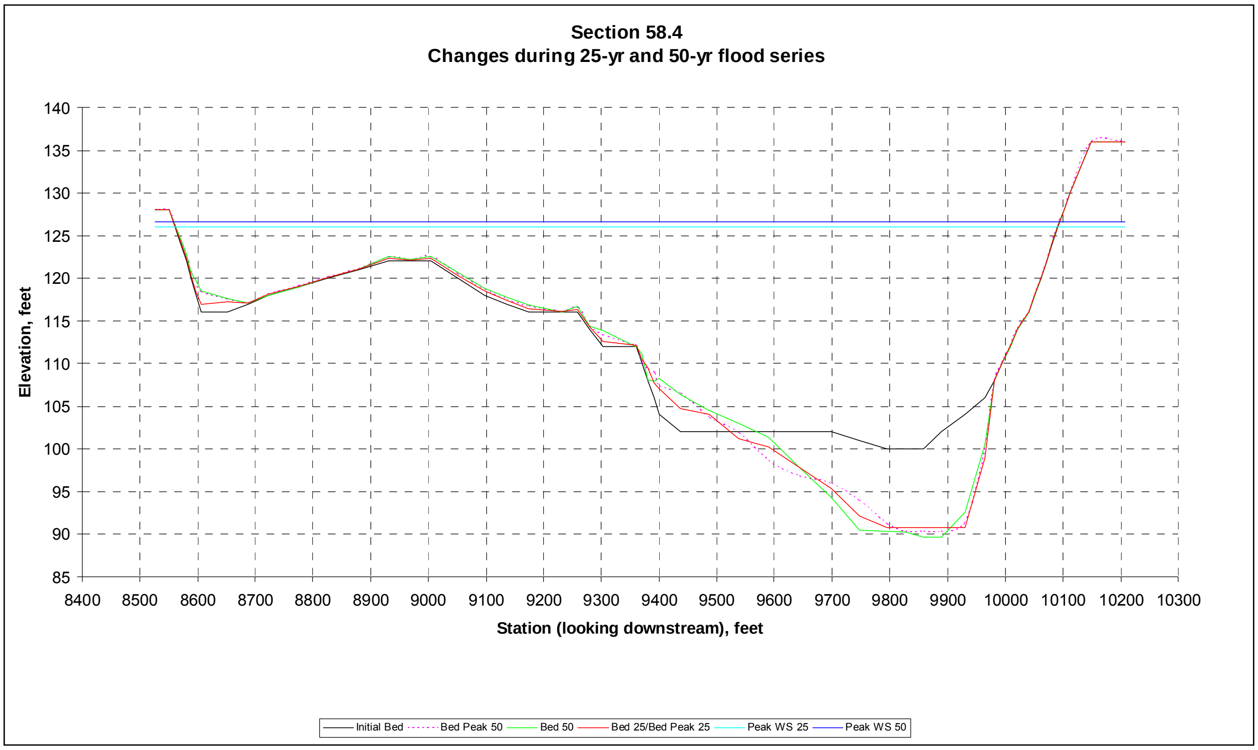

Section 57.5
Changes during 25-yr and 50-yr flood series
Elevation, feet
135
130
125
120
115
110
105
100
95
90
85
7800
7900
8000
8100
8200
8300
8400
8500
8600
8700
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50


Section 57.7
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
135
130
125
120
115
110
105
100
95
90
85
7100
7200
7300
7400
7500
7600
7700
7800
7900
8000
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

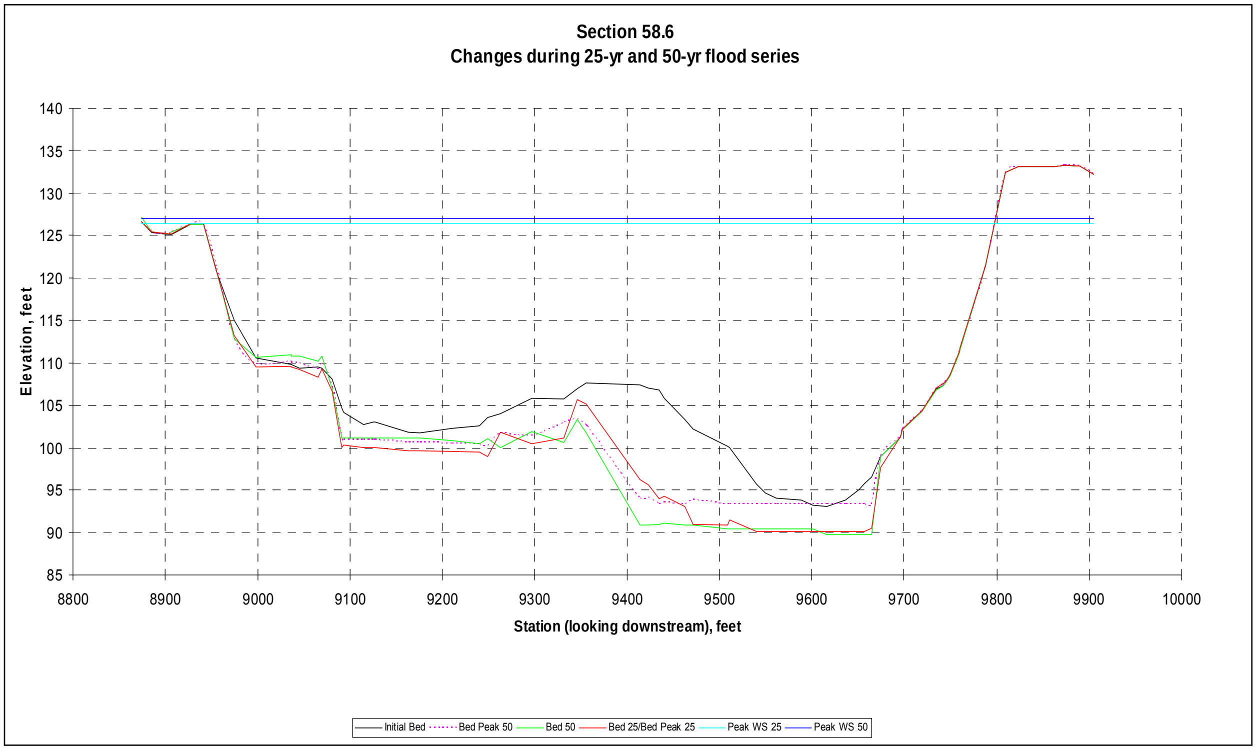

Section 57.9
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
135
130
125
120
115
110
105
100
95
90
85
7700
7800
7900
8000
8100
8200
8300
8400
8500
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50


Section 58.1
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

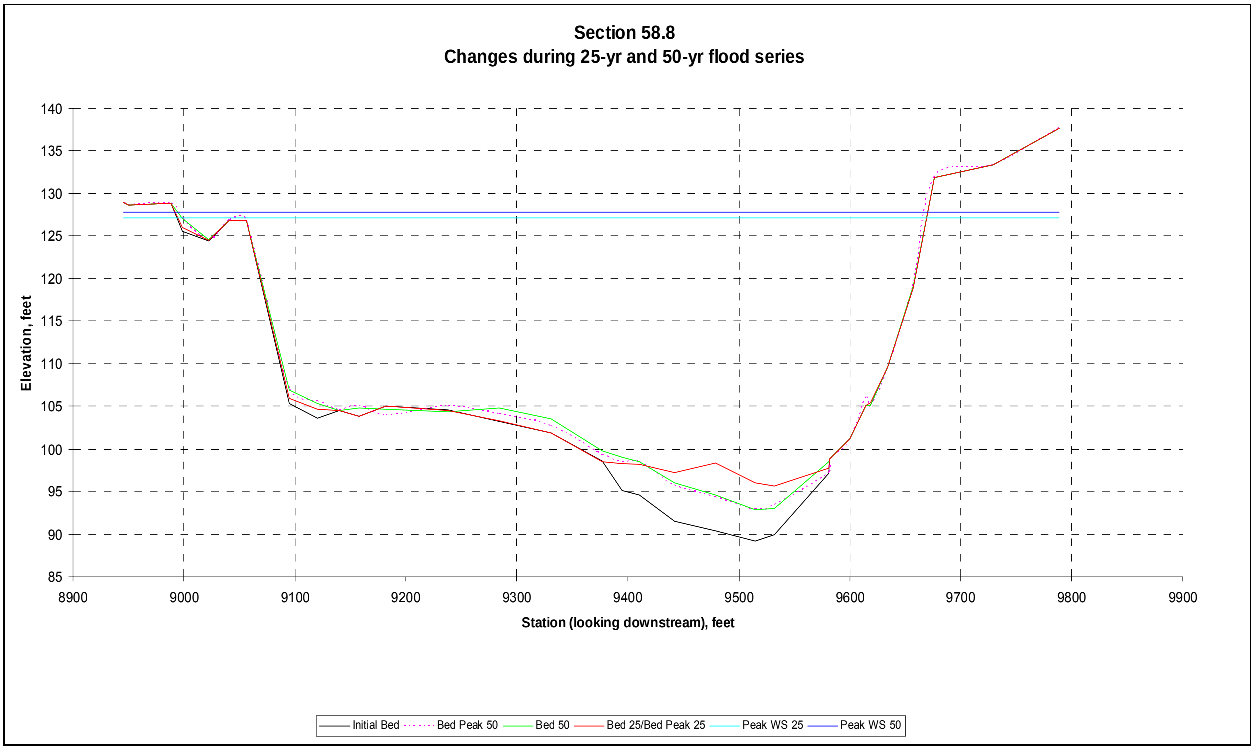

Section 58.3
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

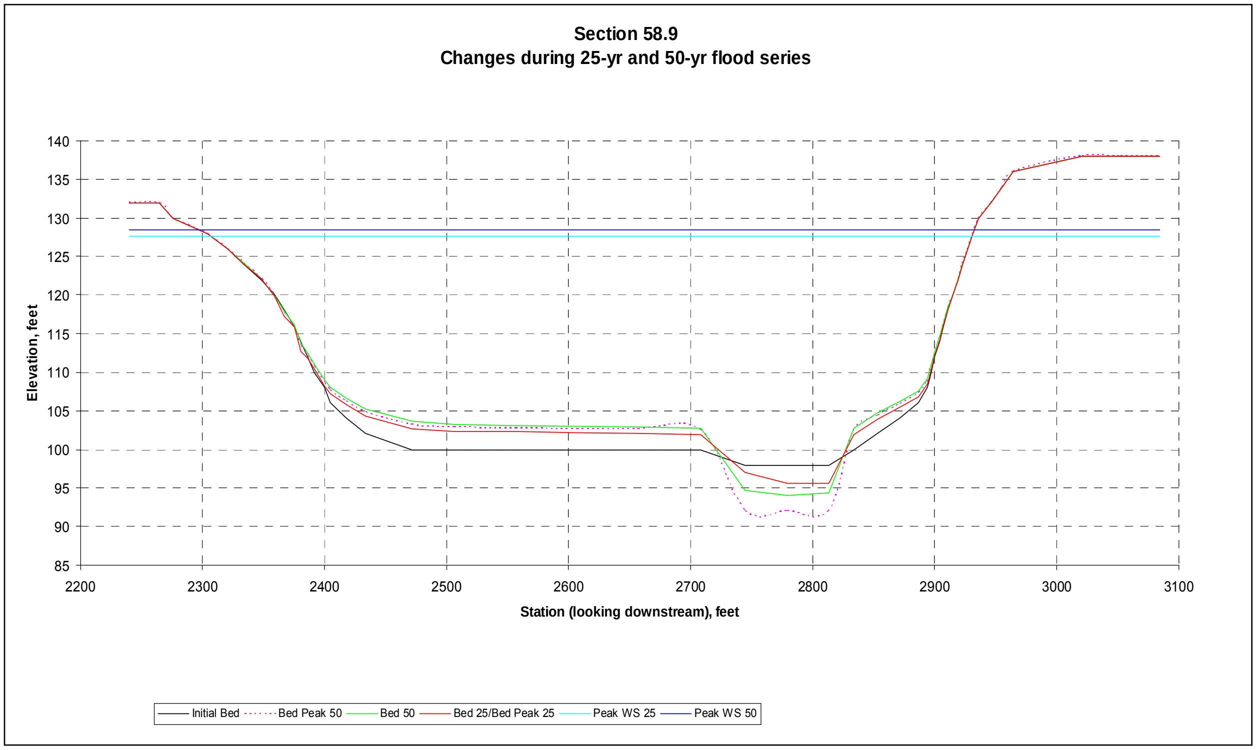


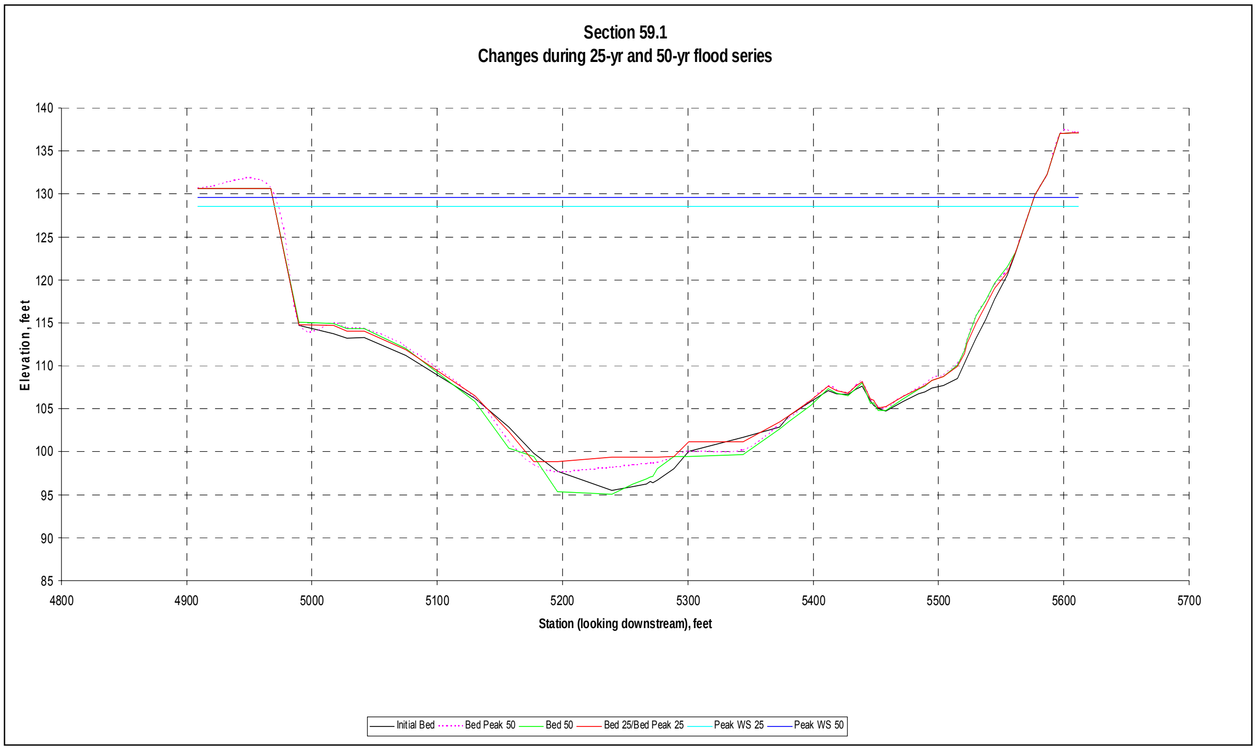
Section 58.4
Changes during 25-yr and 50-yr flood series
Elevation, feet
140
135
130
125
120
115
110
105
100
95
90
85
8400
8500
8600
8700
8800
8900
9000
9100
9200
9300
9400
9500
9600
9700
9800
9900
10000
10100
10200
10300
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

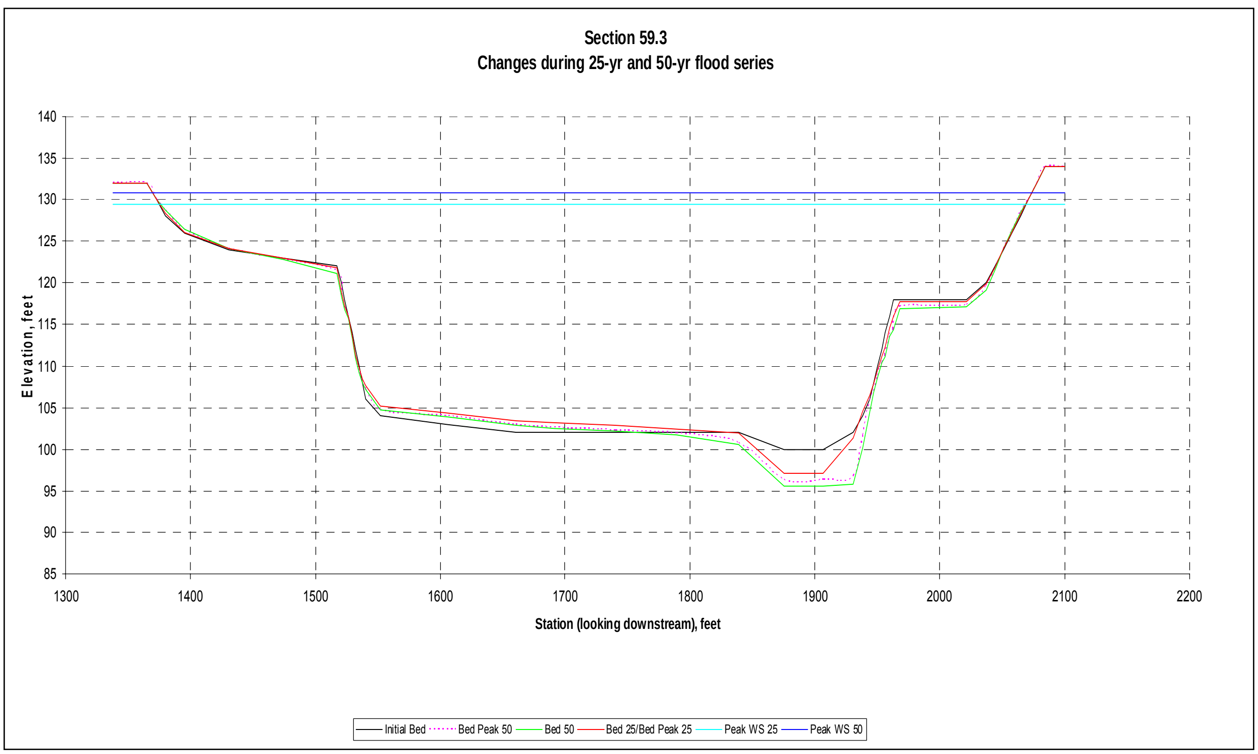


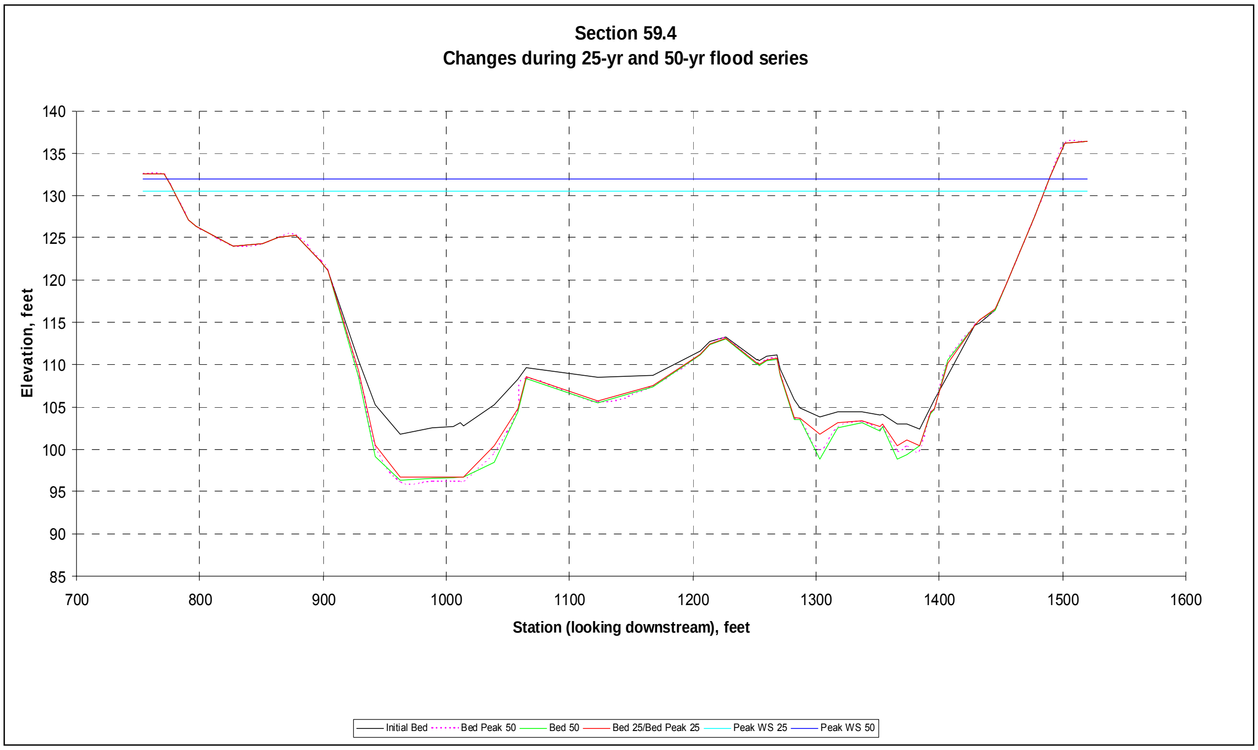
Section 58.6
Changes during 25-yr and 50-yr flood series
Elevation, feet
140
135
130
125
120
115
110
105
100
95
90
85
8800
8900
9000
9100
9200
9300
9400
9500
9600
9700
9800
9900
10000
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

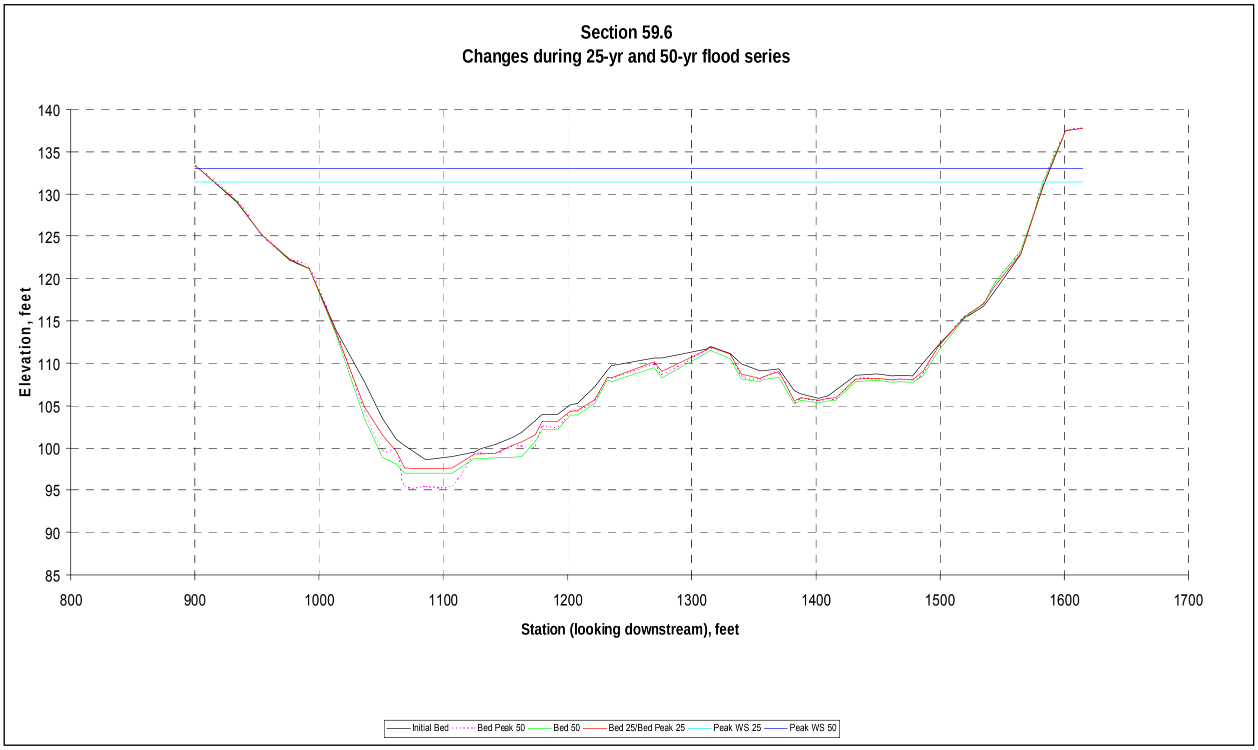

Section 58.8
Changes during 25-yr and 50-yr flood series
Elevation, feet
140
135
130
125
120
115
110
105
100
95
90
85
8900
9000
9100
9200
9300
9400
9500
9600
9700
9800
9900
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

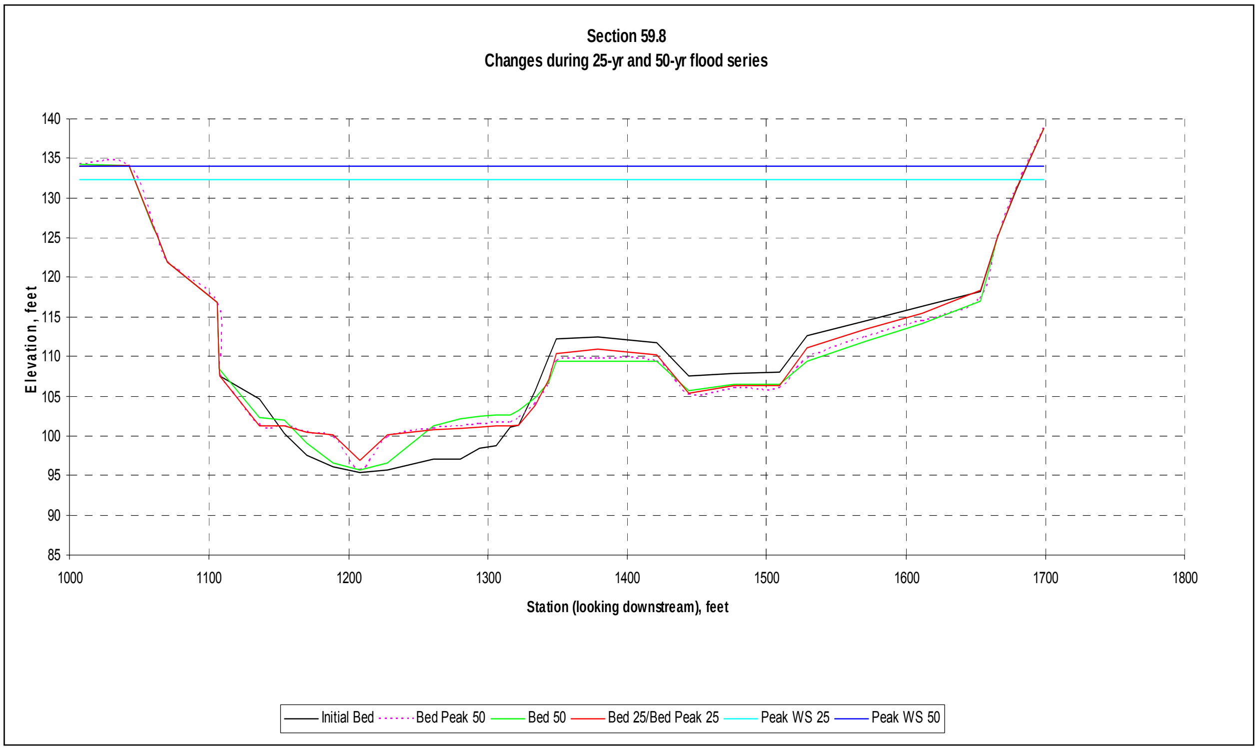

Section 58.9
Changes during 25-yr and 50-yr flood series
Elevation, feet
140
135
130
125
120
115
110
105
100
95
90
85
2200
2300
2400
2500
2600
2700
2800
2900
3000
3100
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

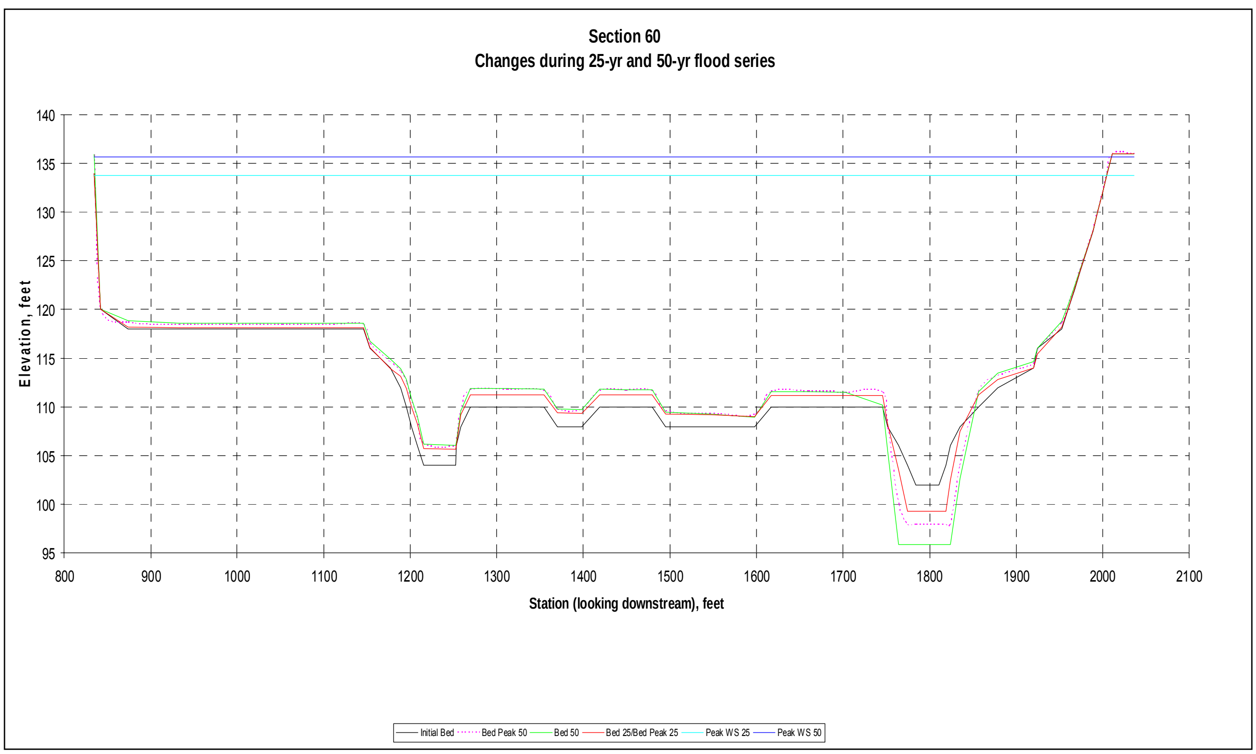

Section 59.1
Changes during 25-yr and 50-yr flood series
Elevation, feet
140
135
130
125
120
115
110
105
100
95
90
85
4800
4900
5000
5100
5200
5300
5400
5500
5600
5700
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

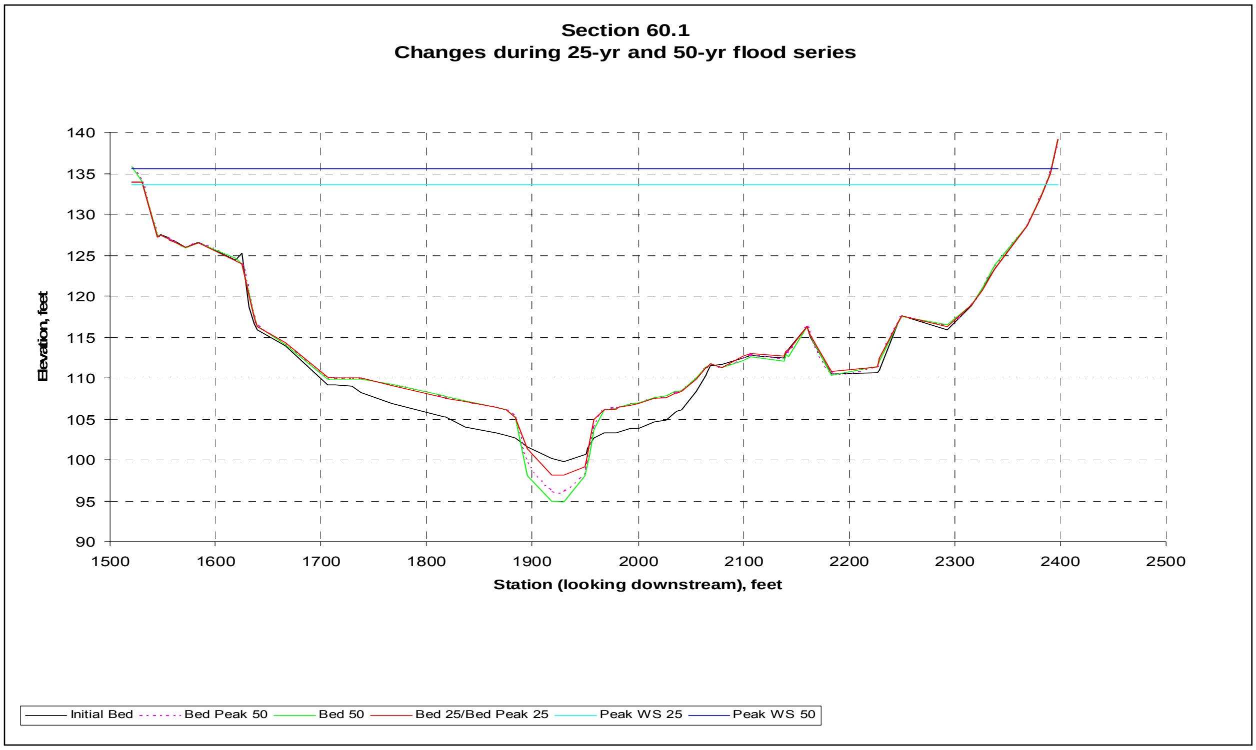

Section 59.3
Changes during 25-yr and 50-yr flood series
Elevation, feet
140
135
130
125
120
115
110
105
100
95
90
85
1300
1400
1500
1600
1700
1800
1900
2000
2100
2200
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

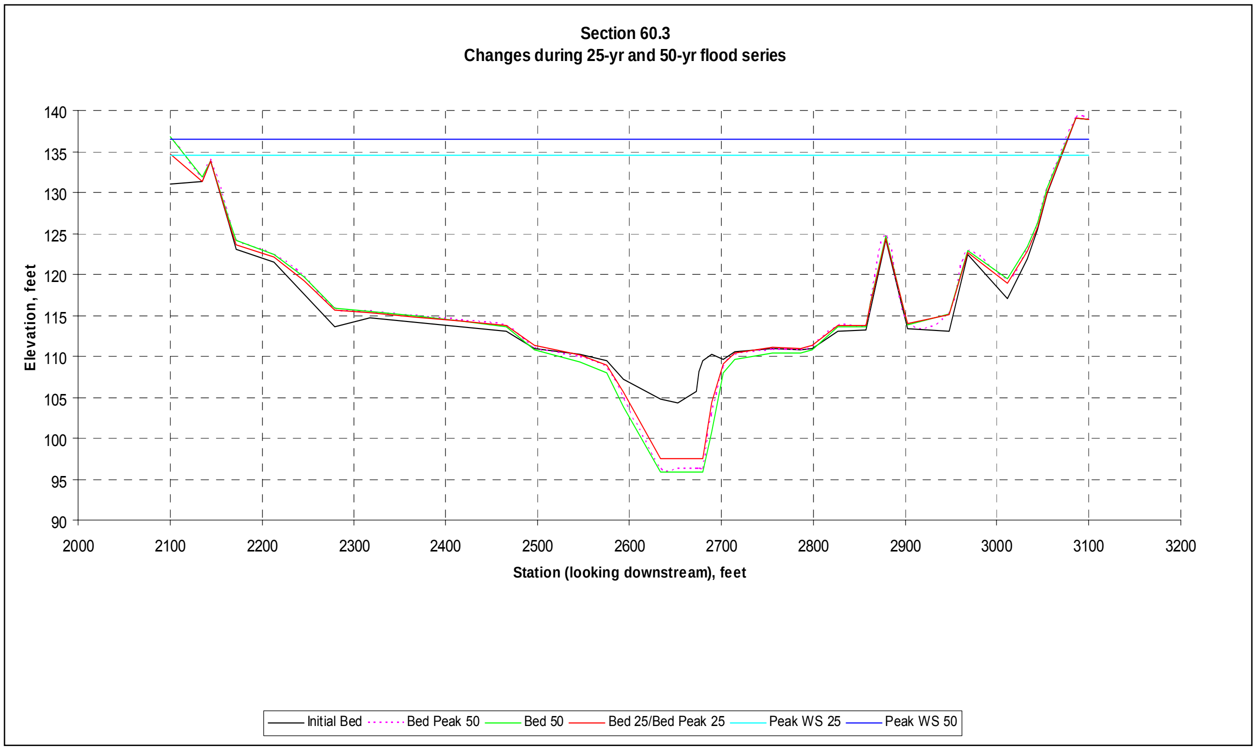

Section 59.4
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

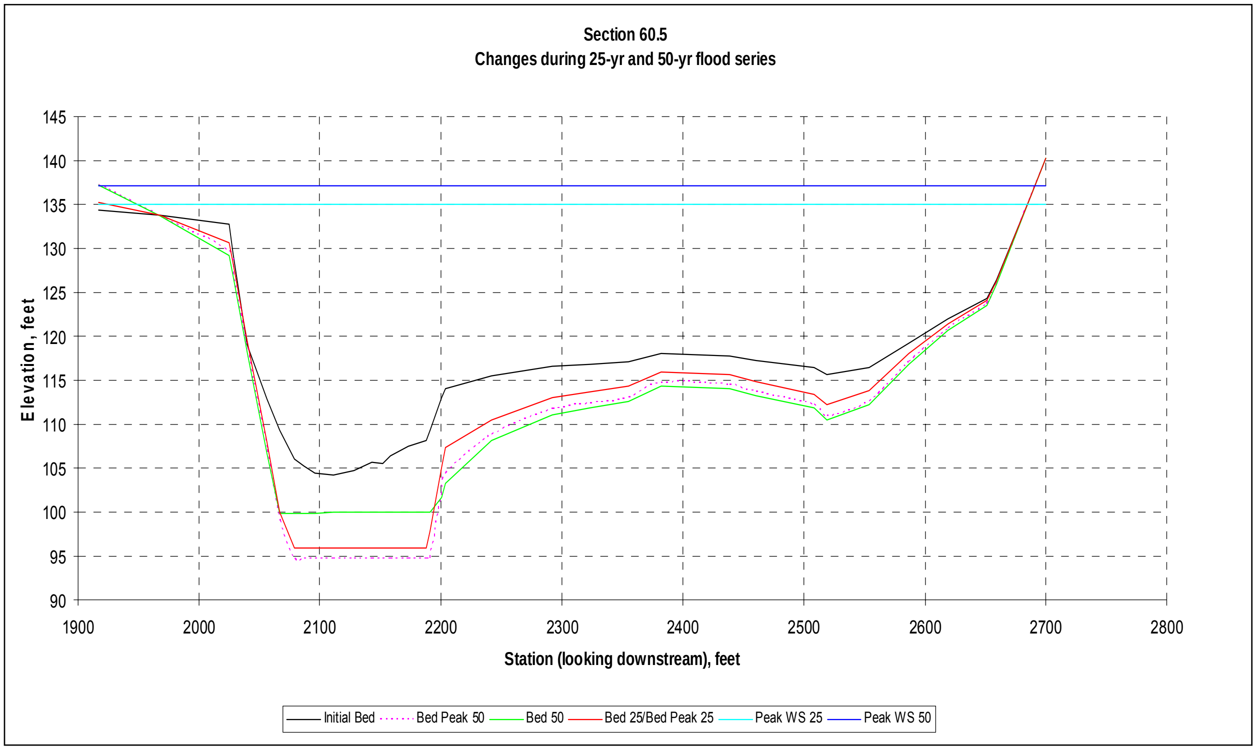

Section 59.6
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

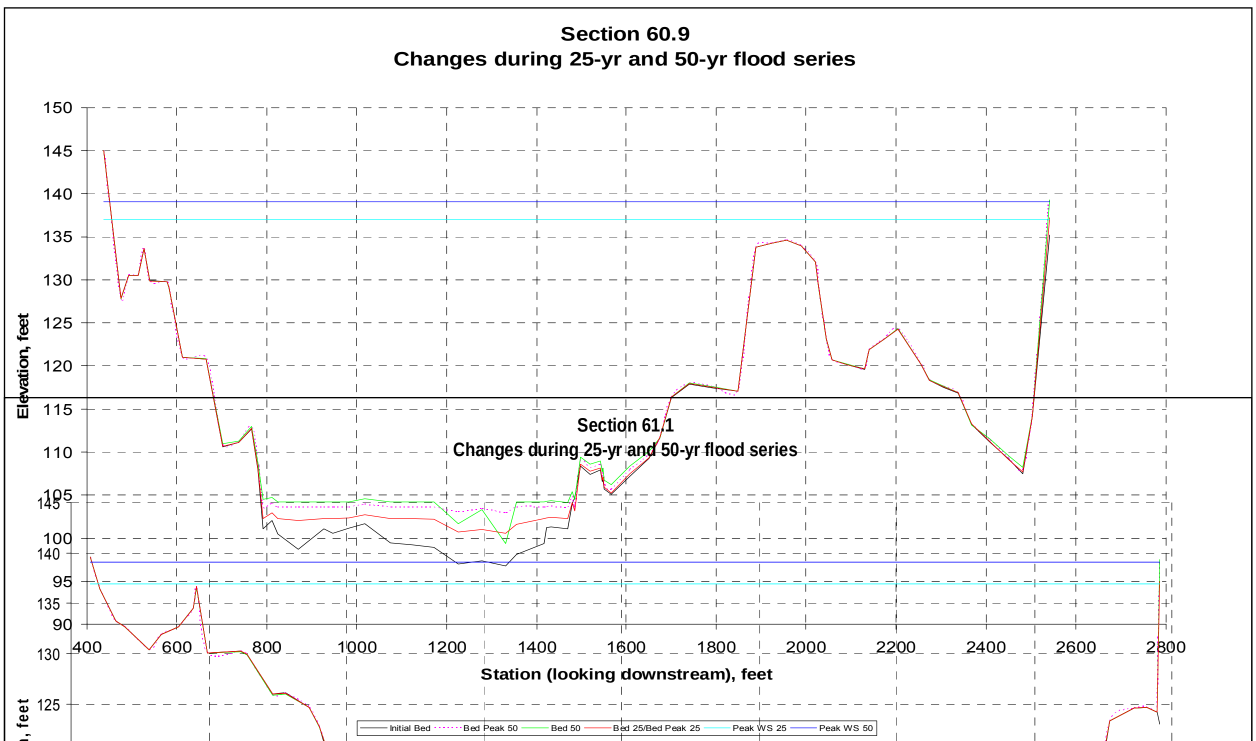

Section 59.8
Changes during 25-yr and 50-yr flood series
Elevation, feet
140
135
130
125
120
115
110
105
100
95
90
85
1000
1100
1200
1300
1400
1500
1600
1700
1800
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

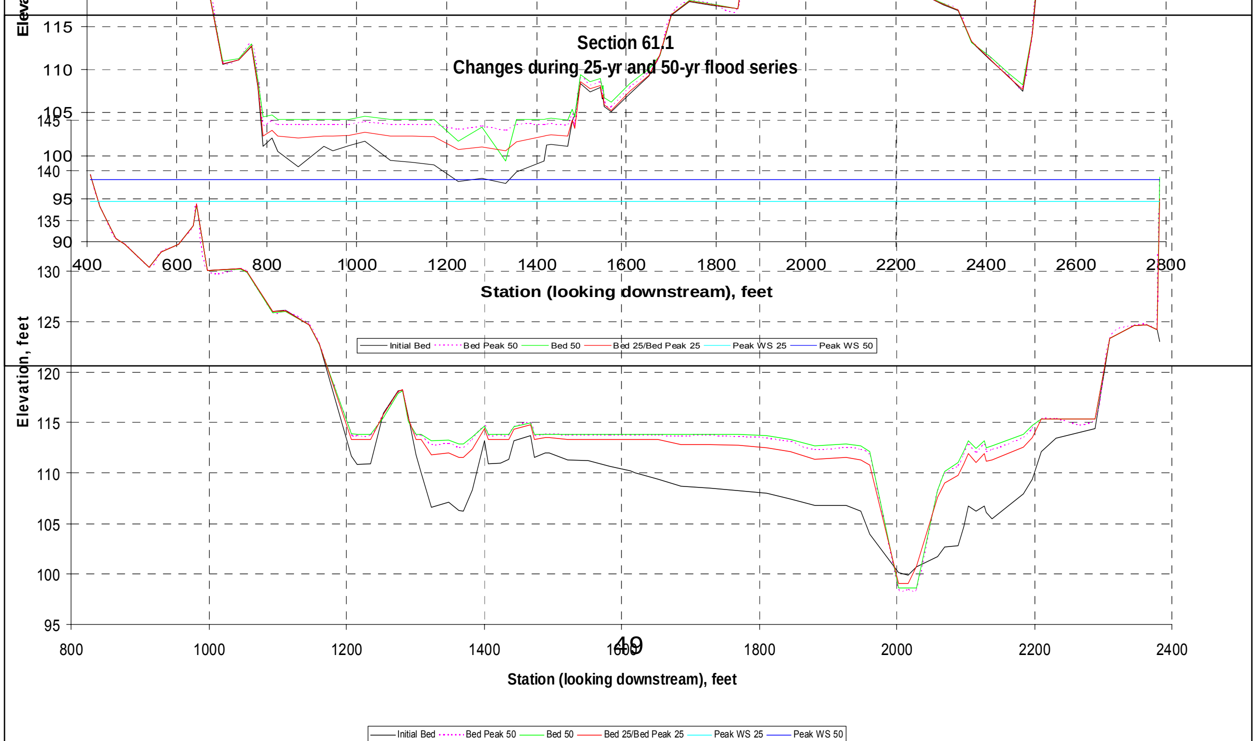

Section 60
Changes during 25-yr and 50-yr flood series
Elevation, feet
140
135
130
125
120
115
110
105
100
95
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
2100
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

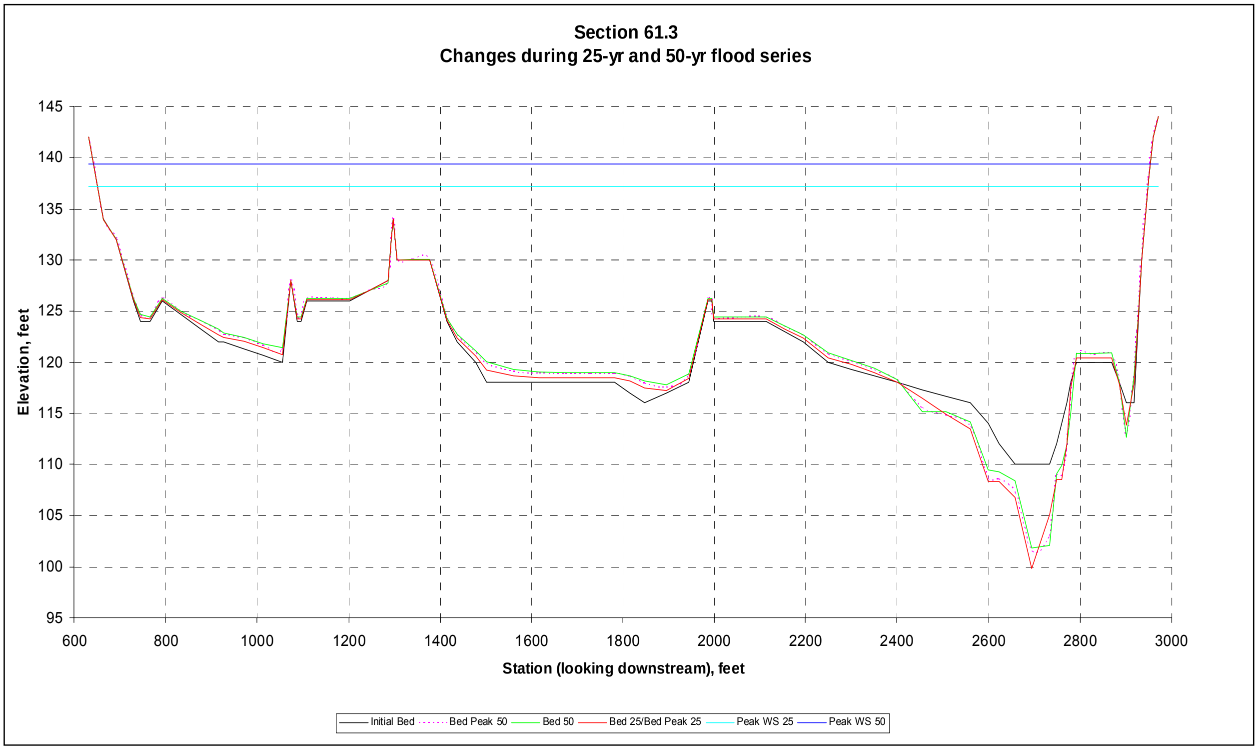

Section 60.1
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
140
135
130
125
120
115
110
105
100
95
90
1500
1600
1700
1800
1900
2000
2100
2200
2300
2400
2500
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

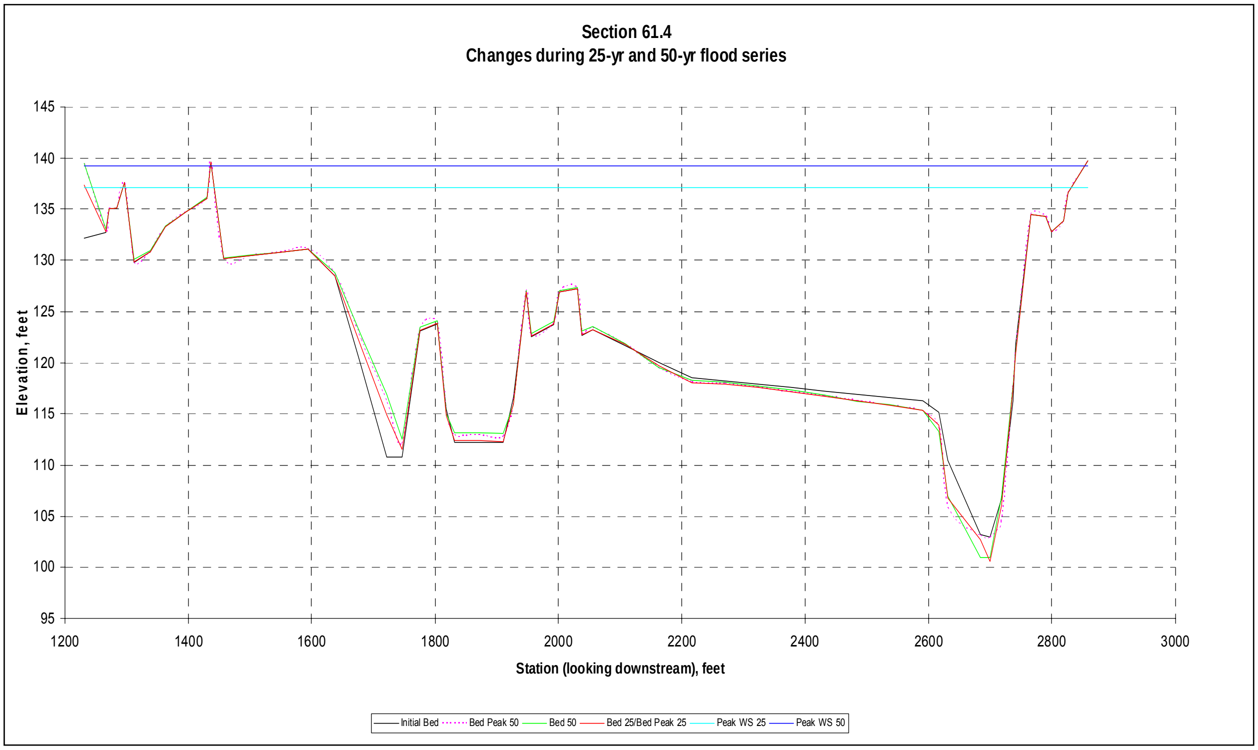

Section 60.3
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
140
135
130
125
120
115
110
105
100
95
90
2000
2100
2200
2300
2400
2500
2600
2700
2800
2900
3000
3100
3200
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

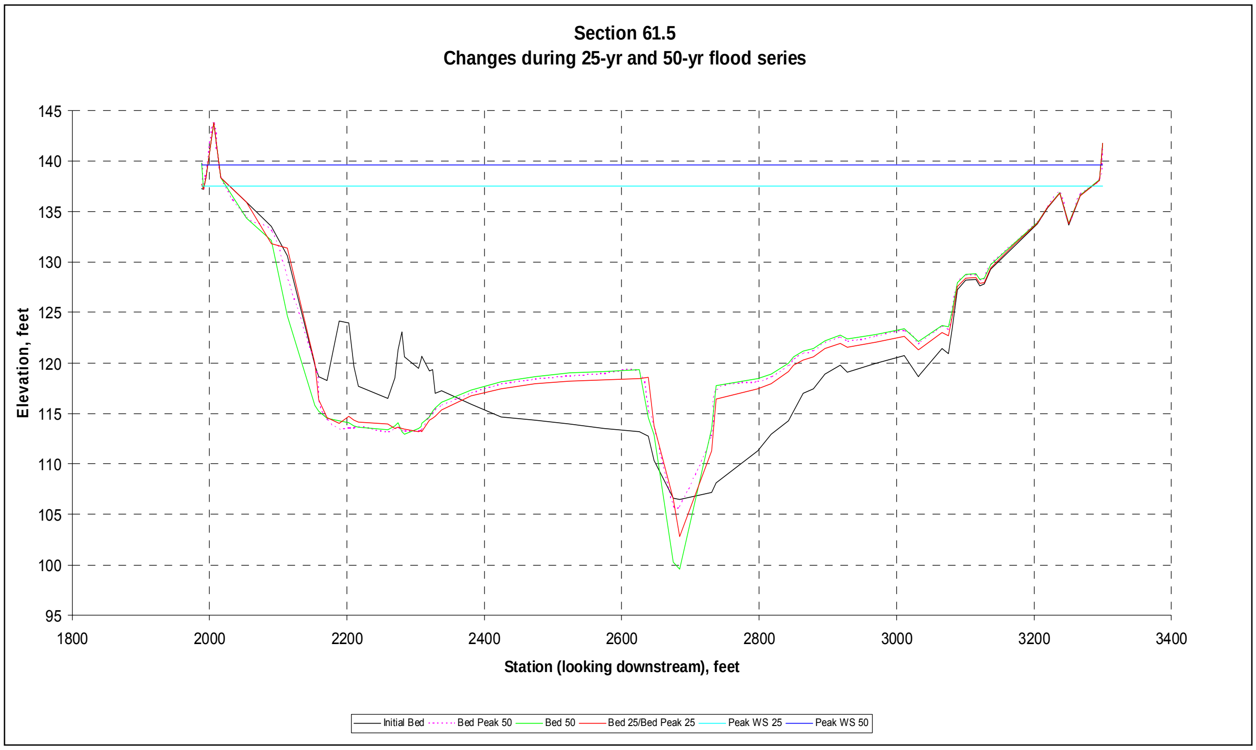

Section 60.5
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

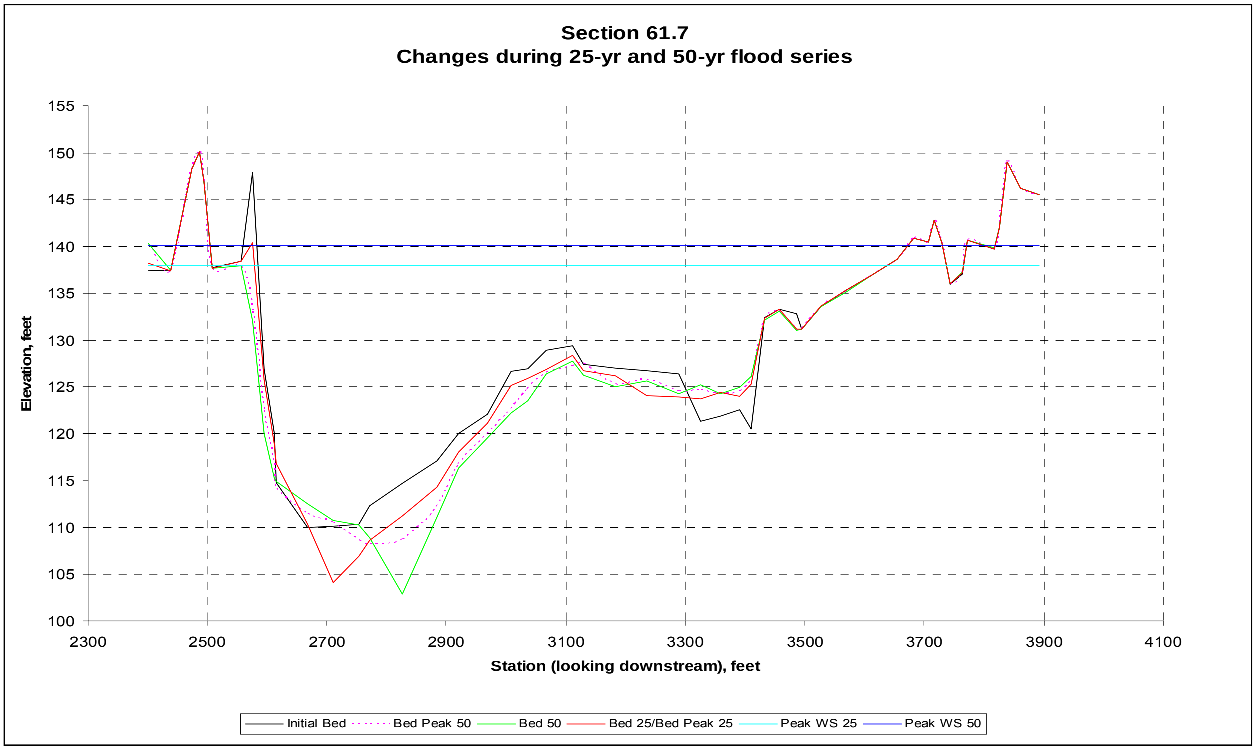

Section 60.9
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

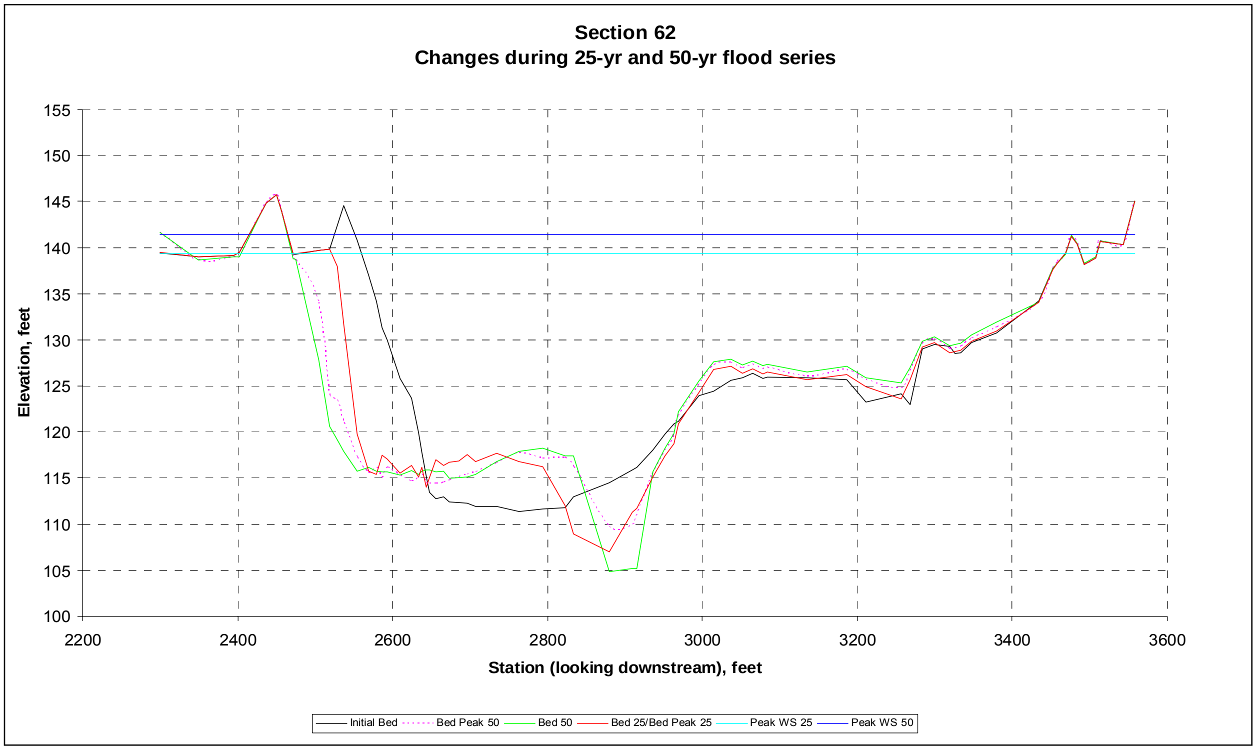

Section 61.1
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

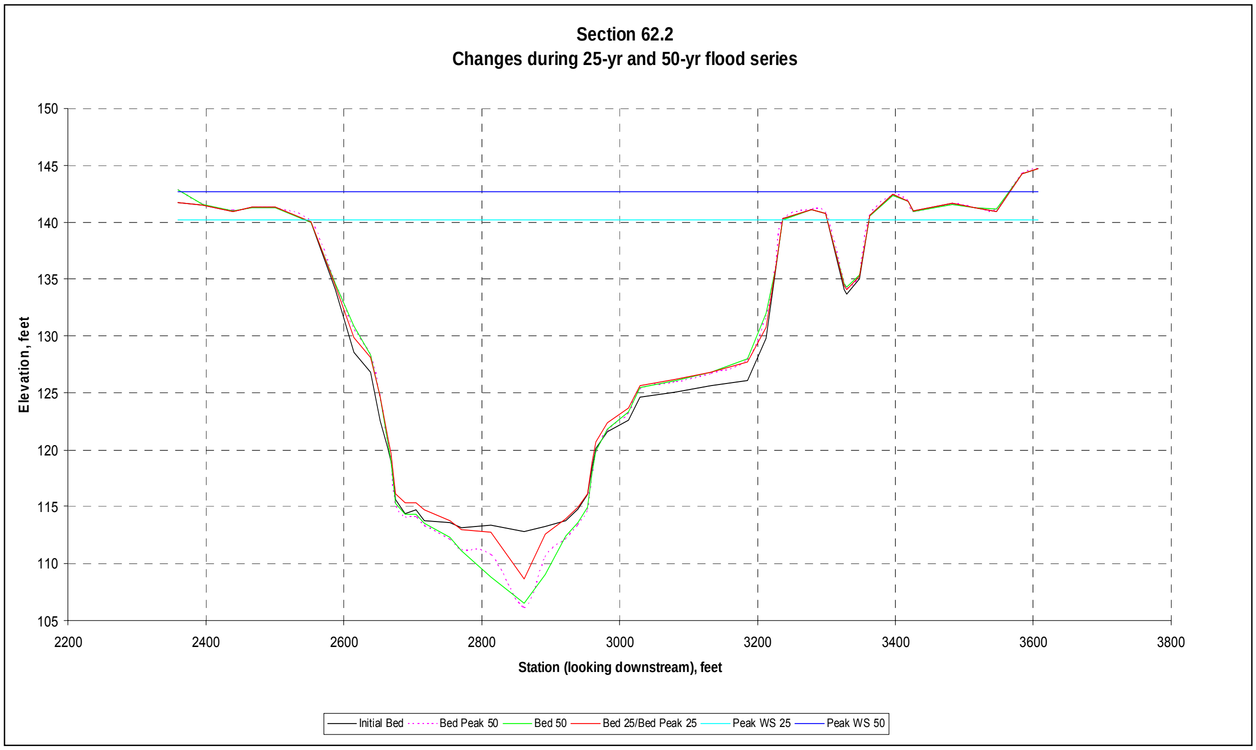

Section 61.3
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50


Section 61.4
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

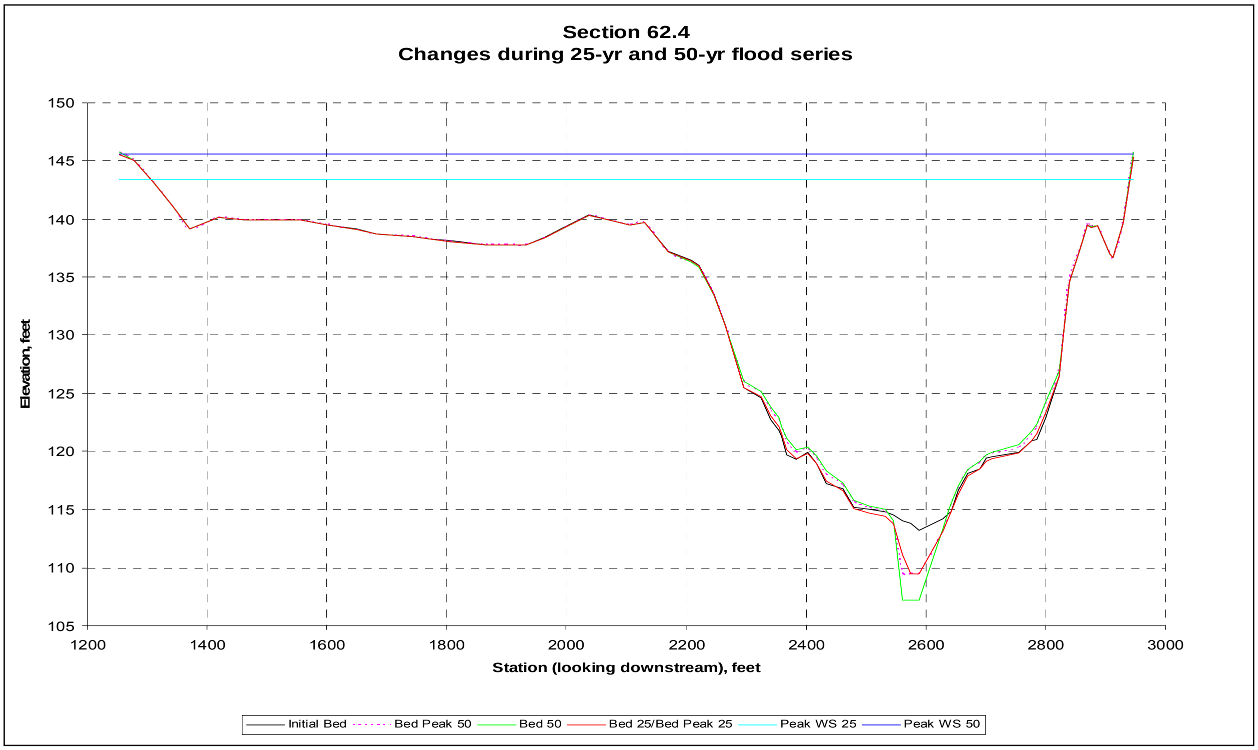

Section 61.5
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

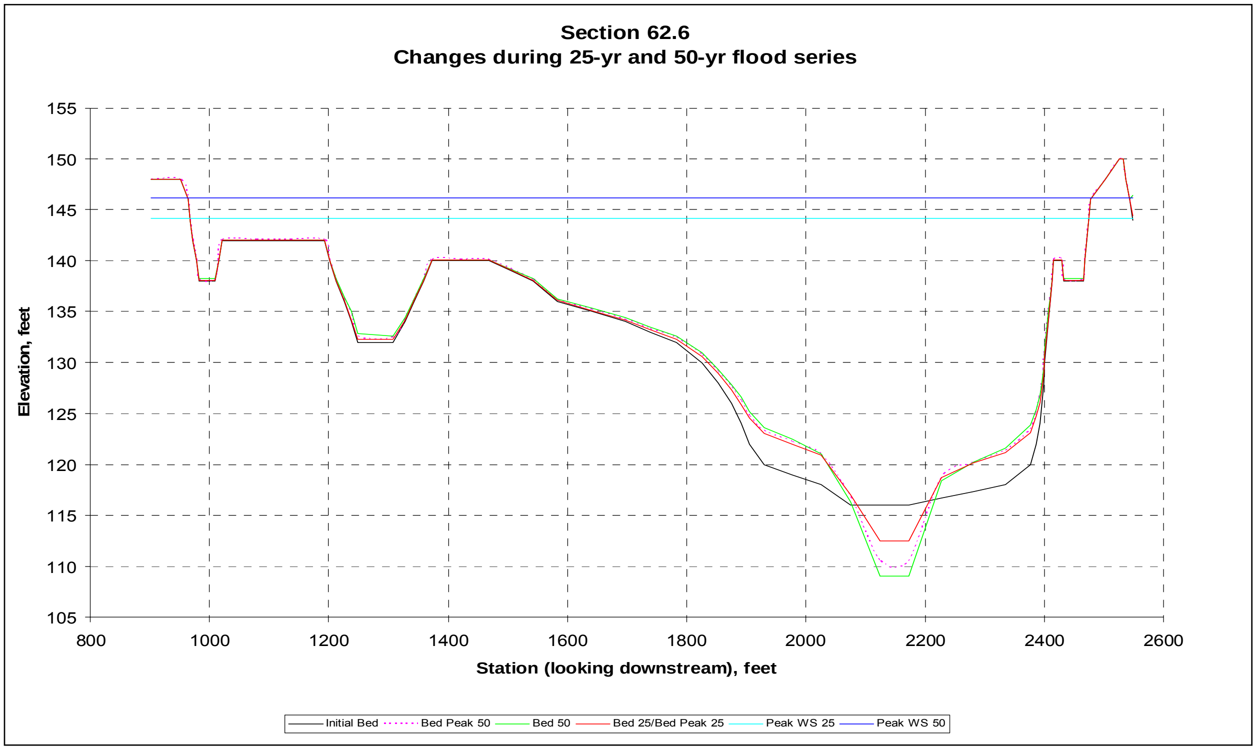

Section 61.7
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

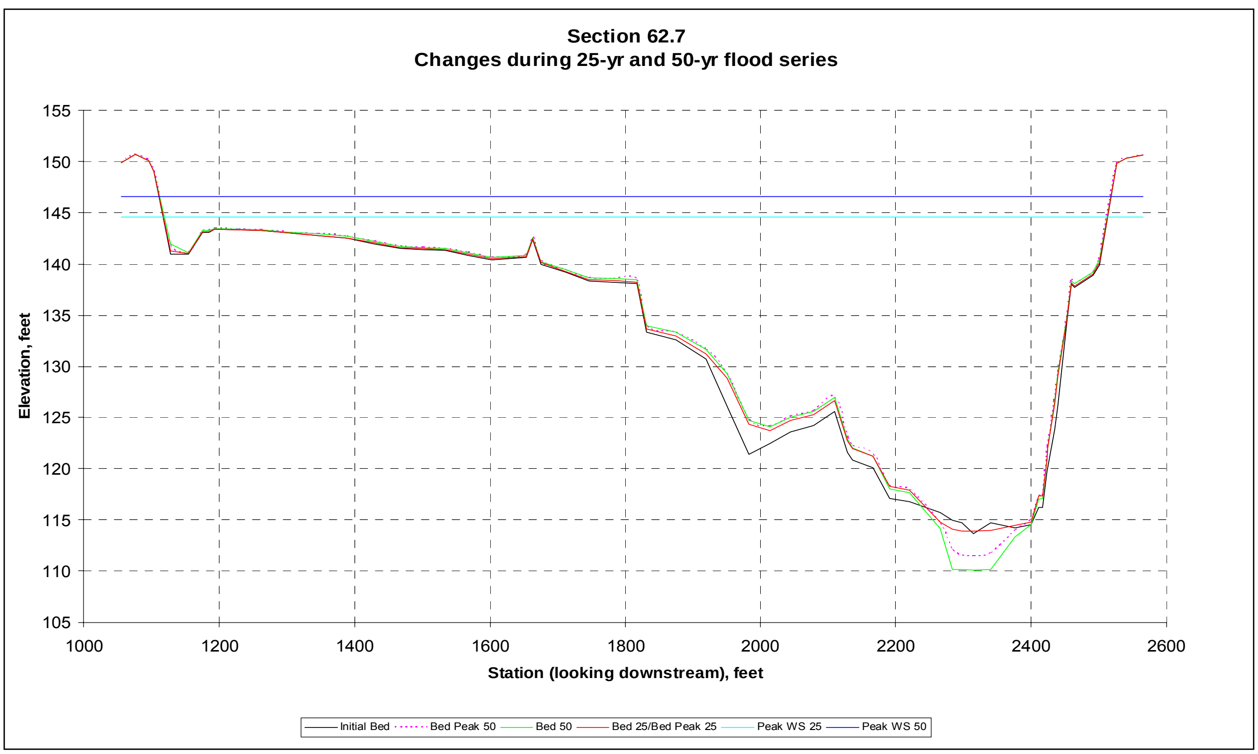

Section 62
Changes during 25-yr and 50-yr flood series
Elevation, feet
155
150
145
140
135
130
125
120
115
110
105
100
2200
2400
2600
2800
3000
3200
3400
3600
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

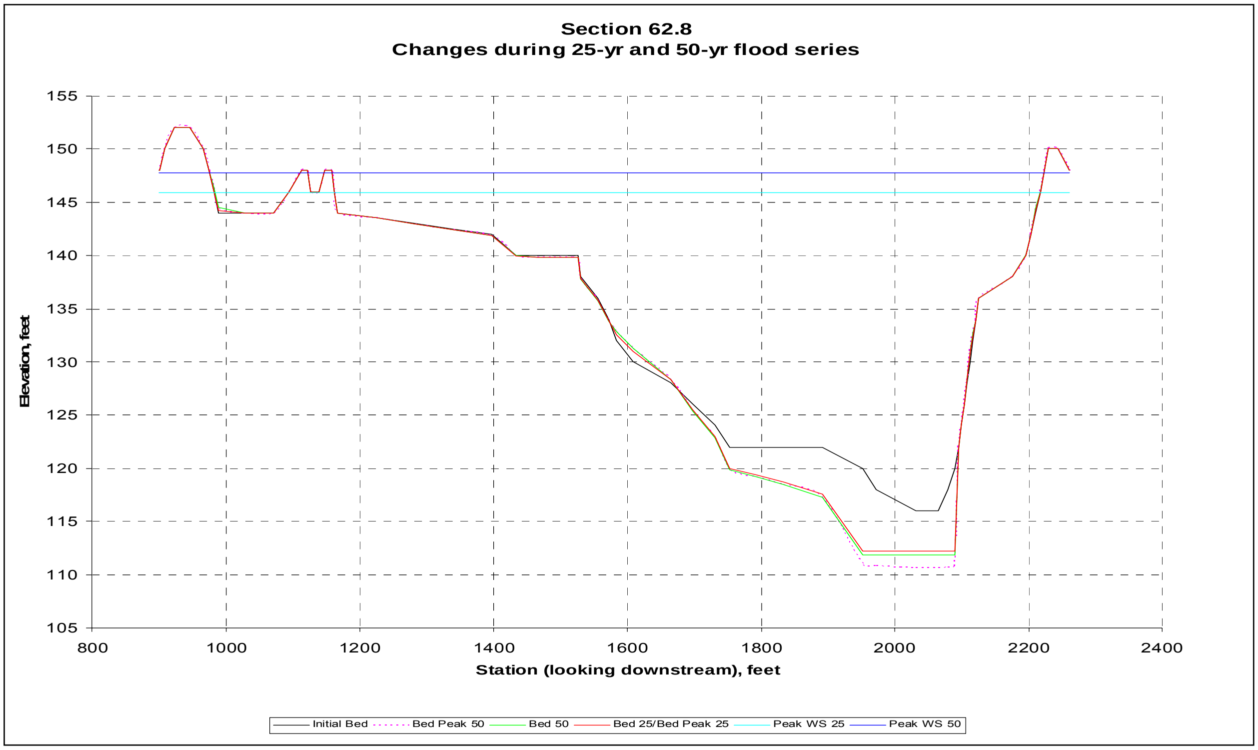

Section 62.2
Changes during 25-yr and 50-yr flood series
Elevation, feet
150
145
140
135
130
125
120
115
110
105
2200
2400
2600
2800
3000
3200
3400
3600
3800
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

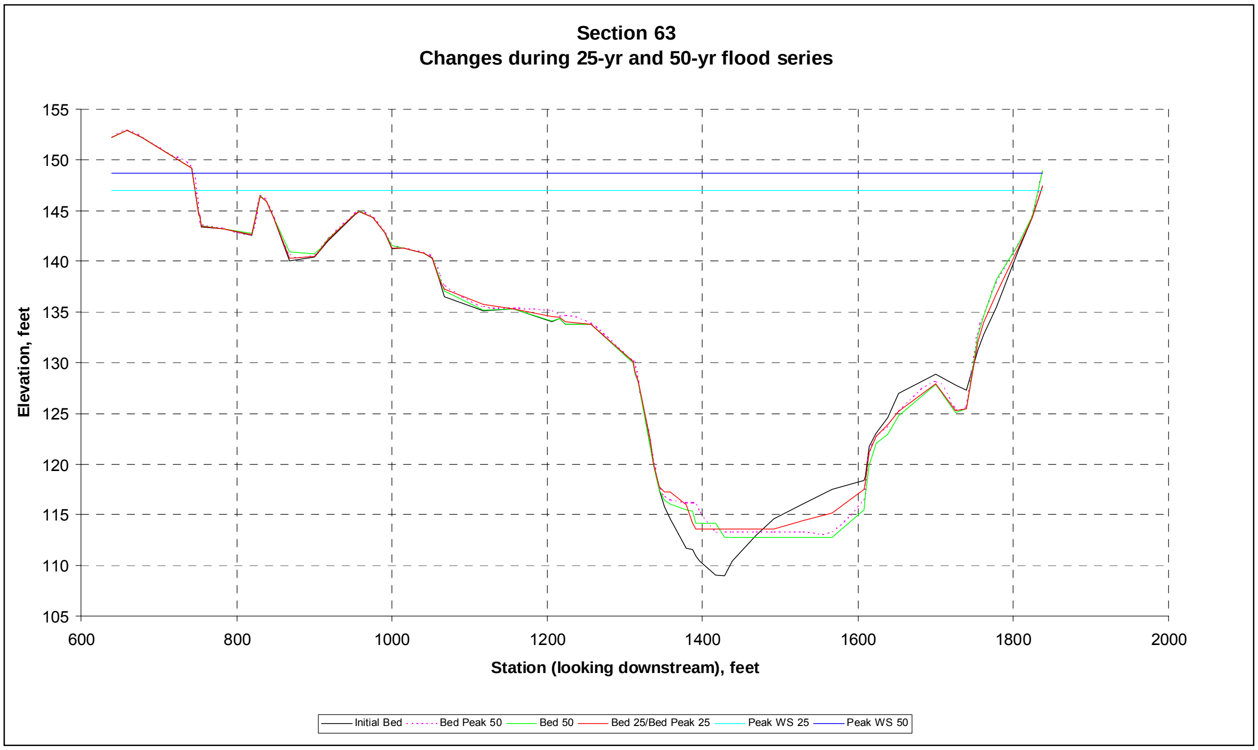

Section 62.3
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
150
145
140
135
130
125
120
115
110
105
100
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
3200
3400
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

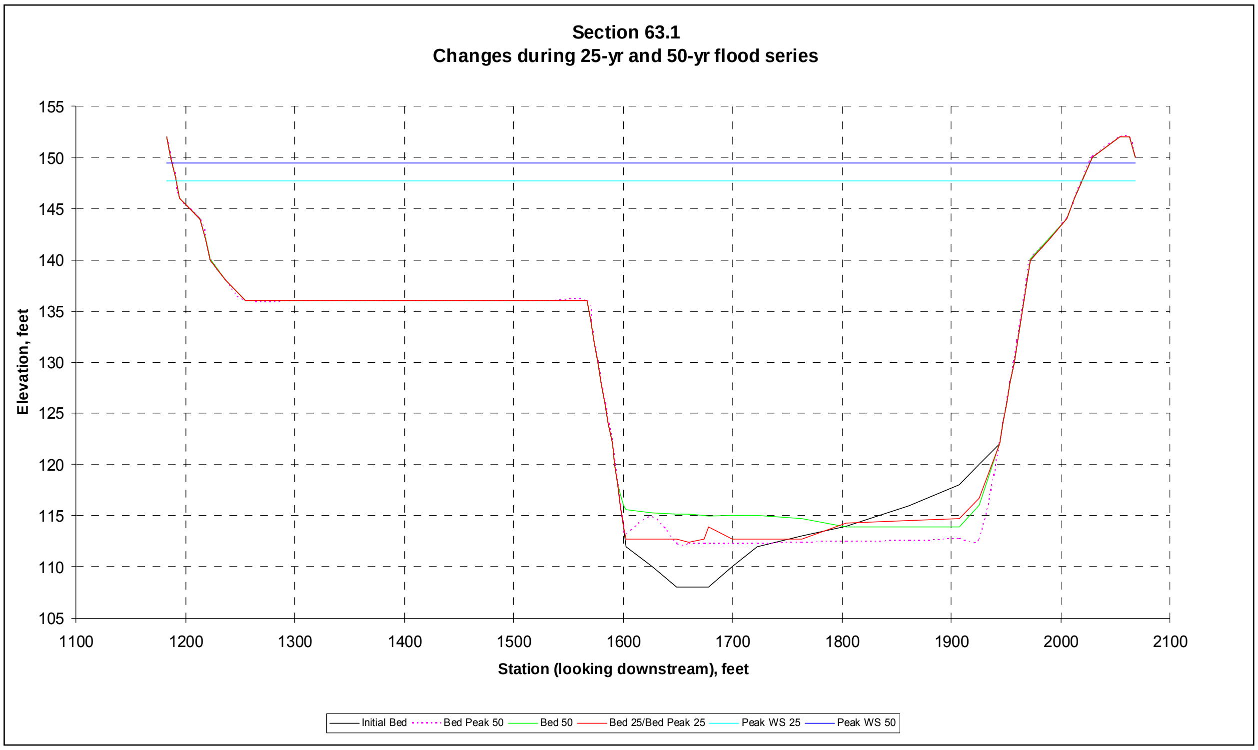

Section 62.4
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
150
145
140
135
130
125
120
115
110
105
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50


Section 62.6
Changes during 25-yr and 50-yr flood series
Elevation, feet
155
150
145
140
135
130
125
120
115
110
105
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

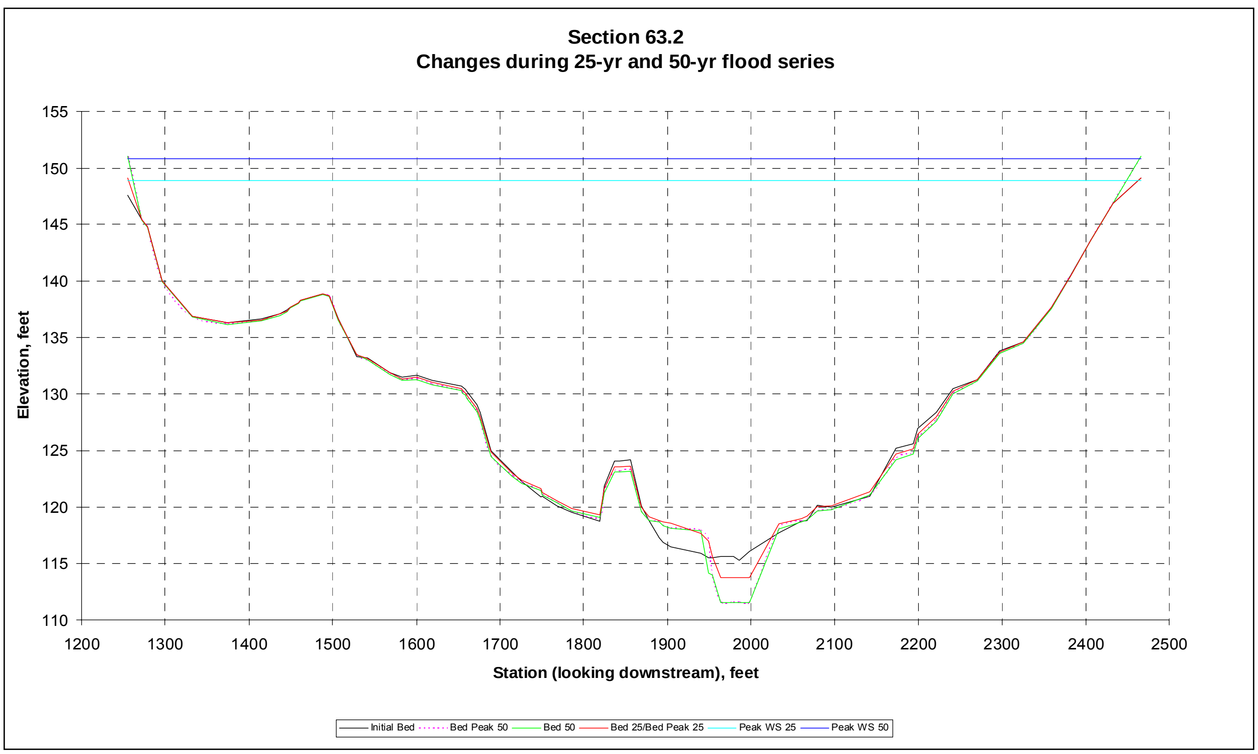

Section 62.7
Changes during 25-yr and 50-yr flood series
Elevation, feet
155
150
145
140
135
130
125
120
115
110
105
1000
1200
1400
1600
1800
2000
2200
2400
2600
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50


Section 62.8
Changes during 25-yr and 50-yr flood series
Elevation, feet
155
150
145
140
135
130
125
120
115
110
105
800
1000
1200
1400
1600
1800
2000
2200
2400
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

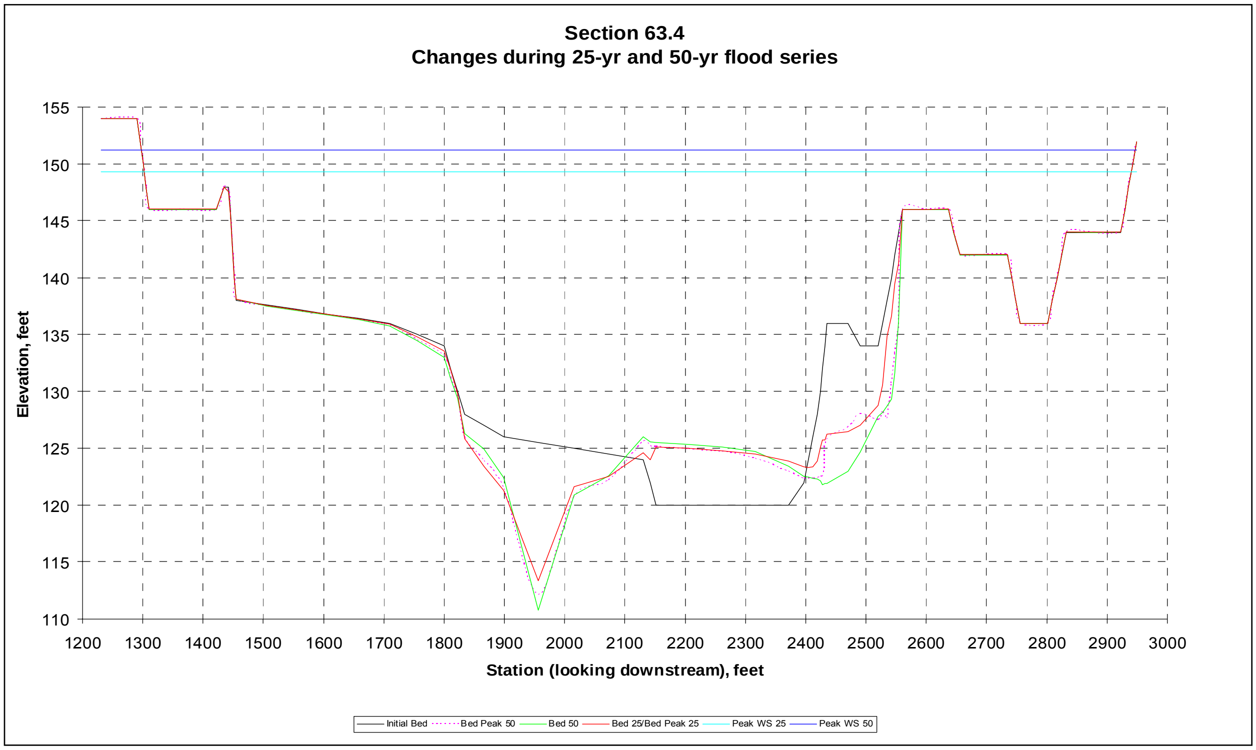

Section 63
Changes during 25-yr and 50-yr flood series
Elevation, feet
155
150
145
140
135
130
125
120
115
110
105
600
800
1000
1200
1400
1600
1800
2000
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

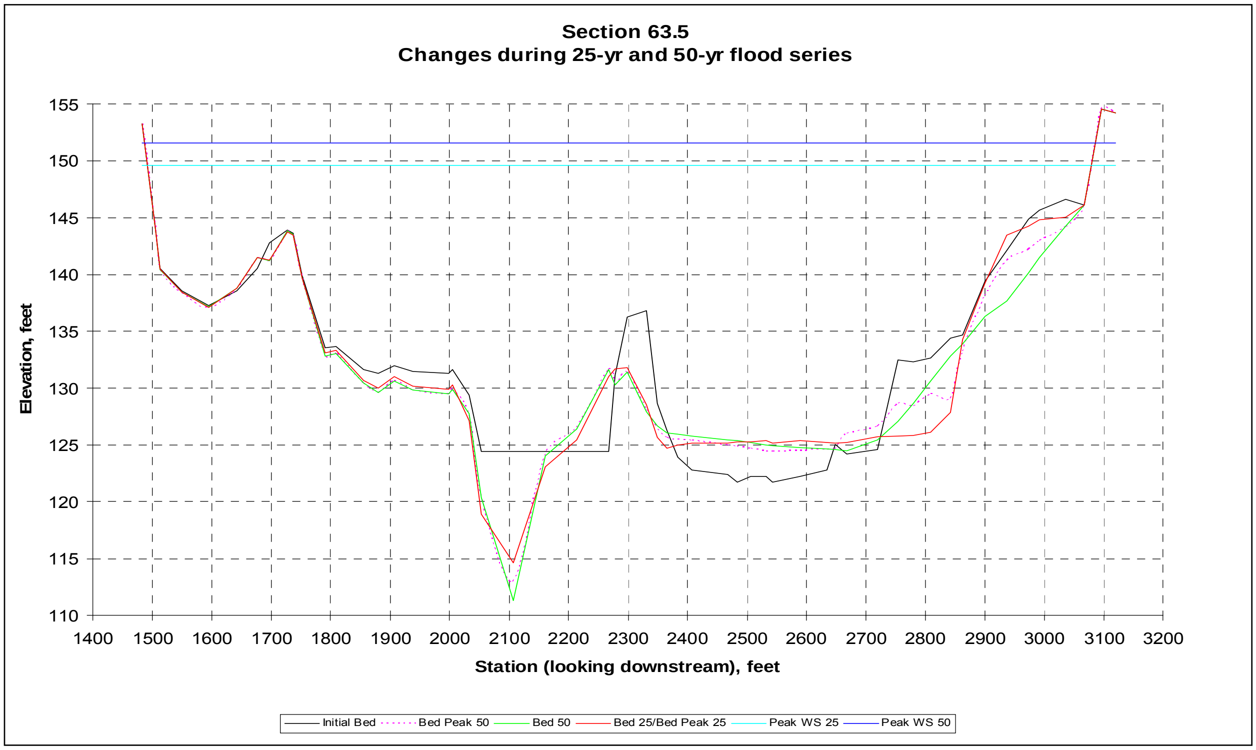


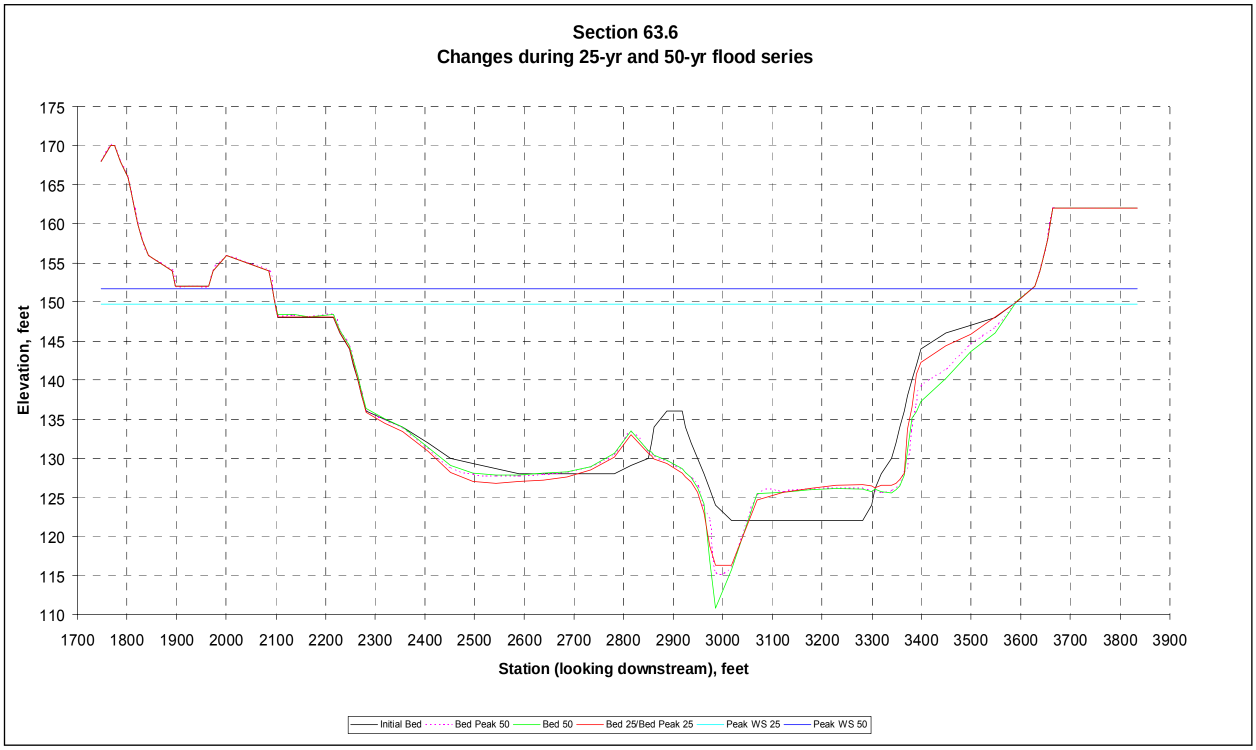
Section 63.1
Changes during 25-yr and 50-yr flood series
Elevation, feet
155
150
145
140
135
130
125
120
115
110
105
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
2100
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

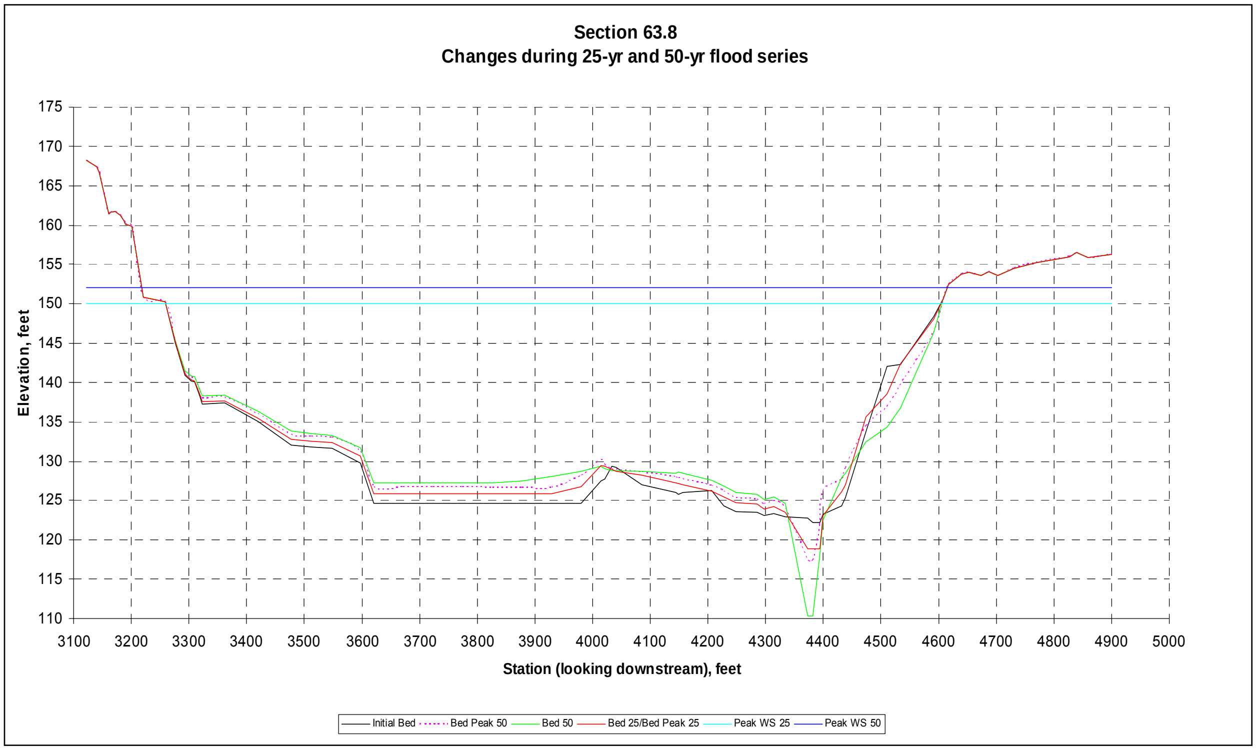


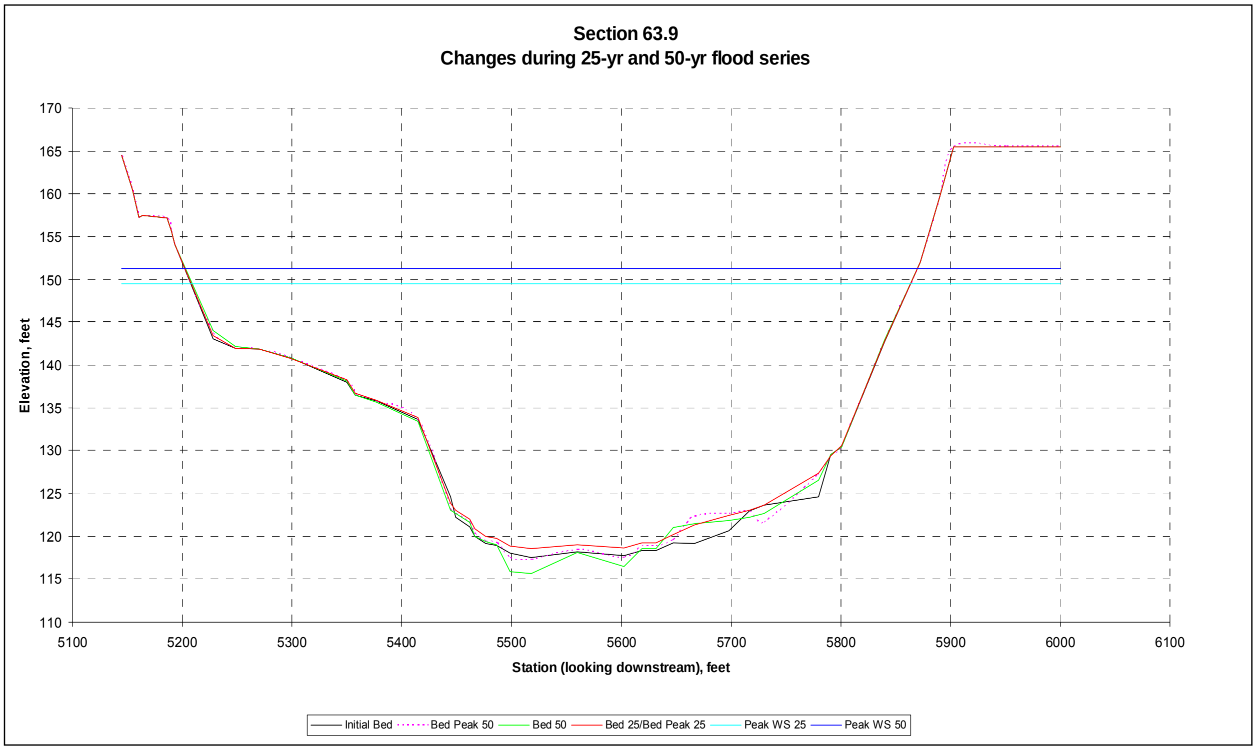
Section 63.2
Changes during 25-yr and 50-yr flood series
Elevation, feet
155
150
145
140
135
130
125
120
115
110
1200
1300
1400
1500
1600
1700
1800
1900
2000
2100
2200
2300
2400
2500
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

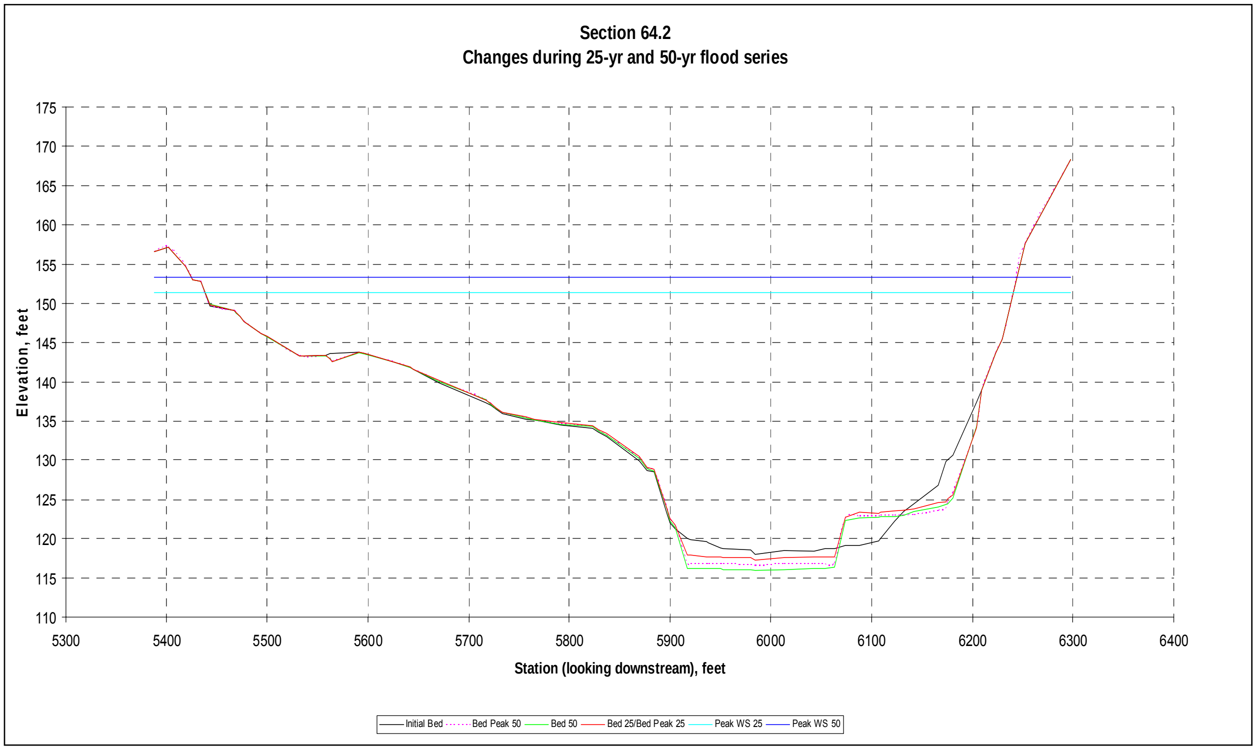

Section 63.4
Changes during 25-yr and 50-yr flood series
Elevation, feet
155
150
145
140
135
130
125
120
115
110
1200
1300
1400
1500
1600
1700
1800
1900
2000
2100
2200
2300
2400
2500
2600
2700
2800
2900
3000
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

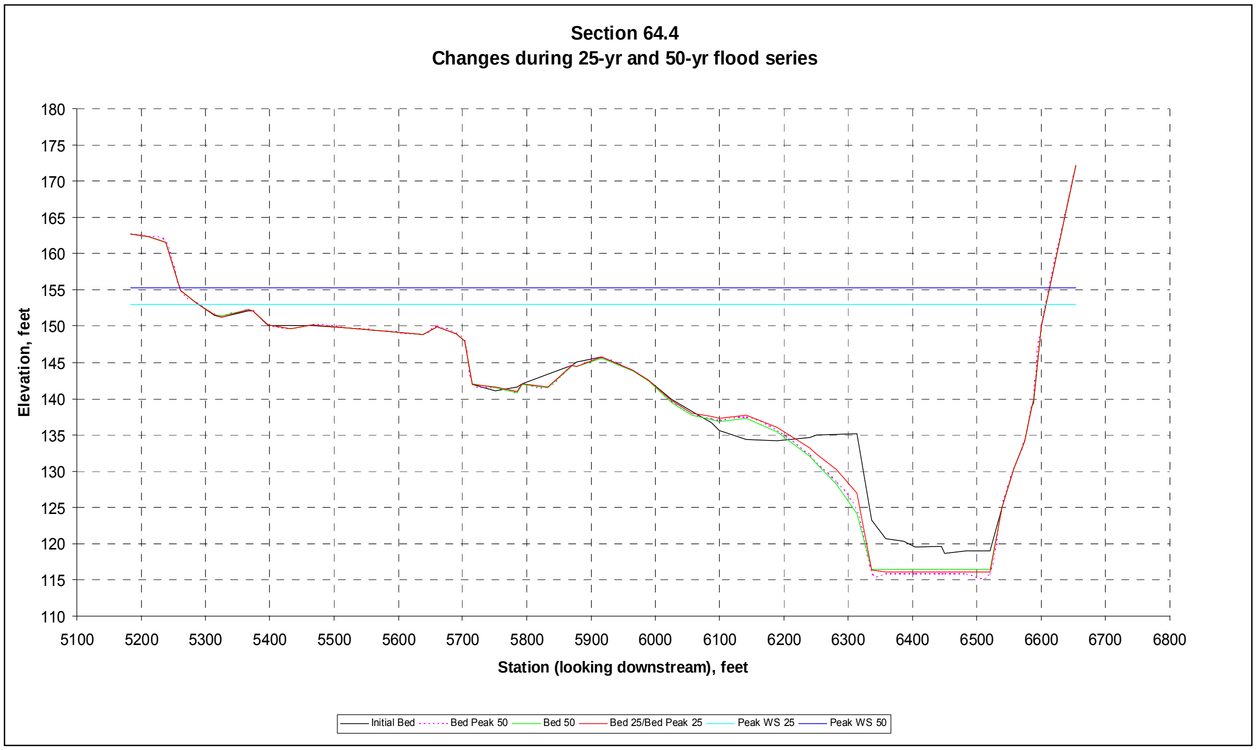

Section 63.5
Changes during 25-yr and 50-yr flood series
Elevation, feet
155
150
145
140
135
130
125
120
115
110
1400
1500
1600
1700
1800
1900
2000
2100
2200
2300
2400
2500
2600
2700
2800
2900
3000
3100
3200
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

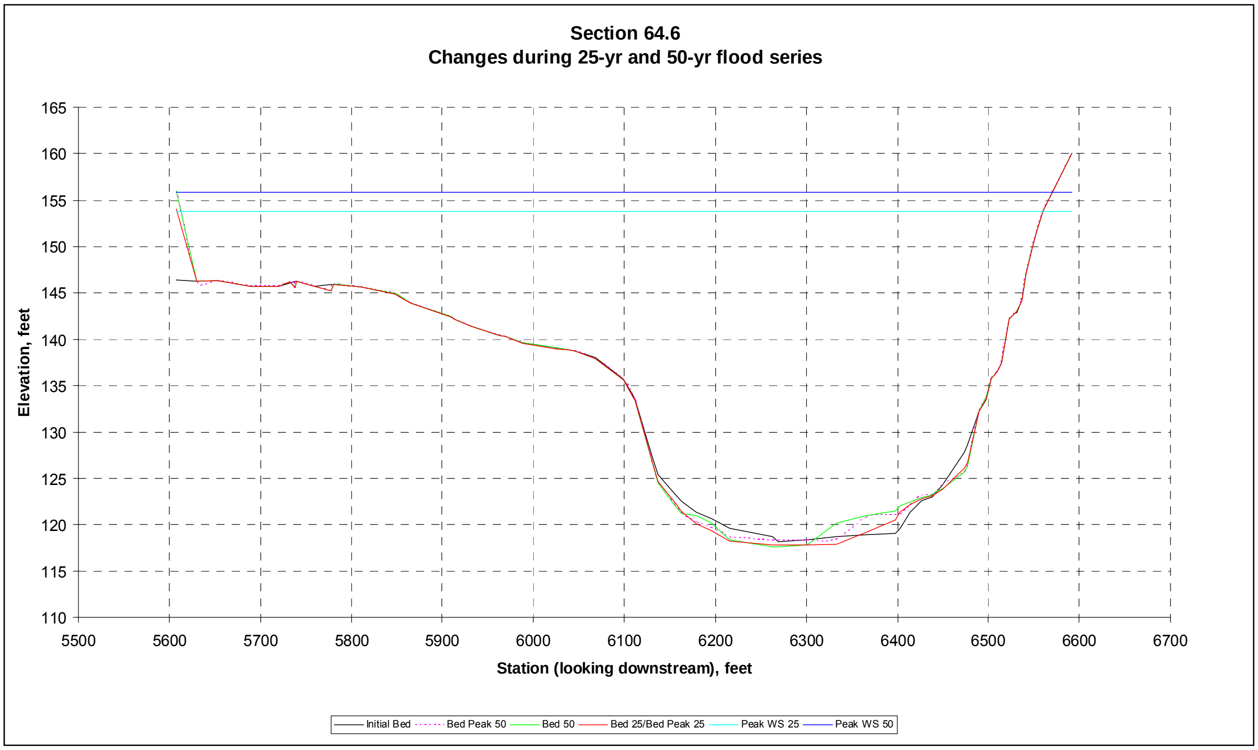

Section 63.6
Changes during 25-yr and 50-yr flood series
Elevation, feet
175
170
165
160
155
150
145
140
135
130
125
120
115
110
1700
1800
1900
2000
2100
2200
2300
2400
2500
2600
2700
2800
2900
3000
3100
3200
3300
3400
3500
3600
3700
3800
3900
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

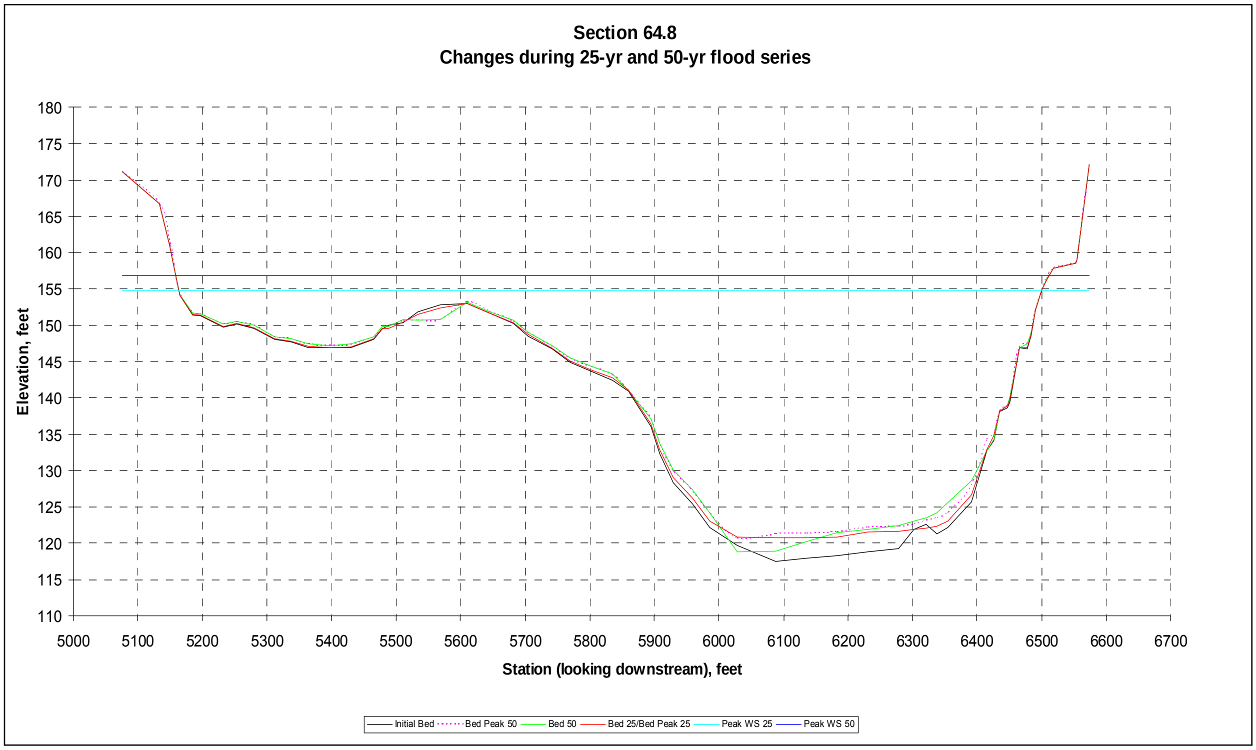

Section 63.8
Changes during 25-yr and 50-yr flood series
Elevation, feet
175
170
165
160
155
150
145
140
135
130
125
120
115
110
3100
3200
3300
3400
3500
3600
3700
3800
3900
4000
4100
4200
4300
4400
4500
4600
4700
4800
4900
5000
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

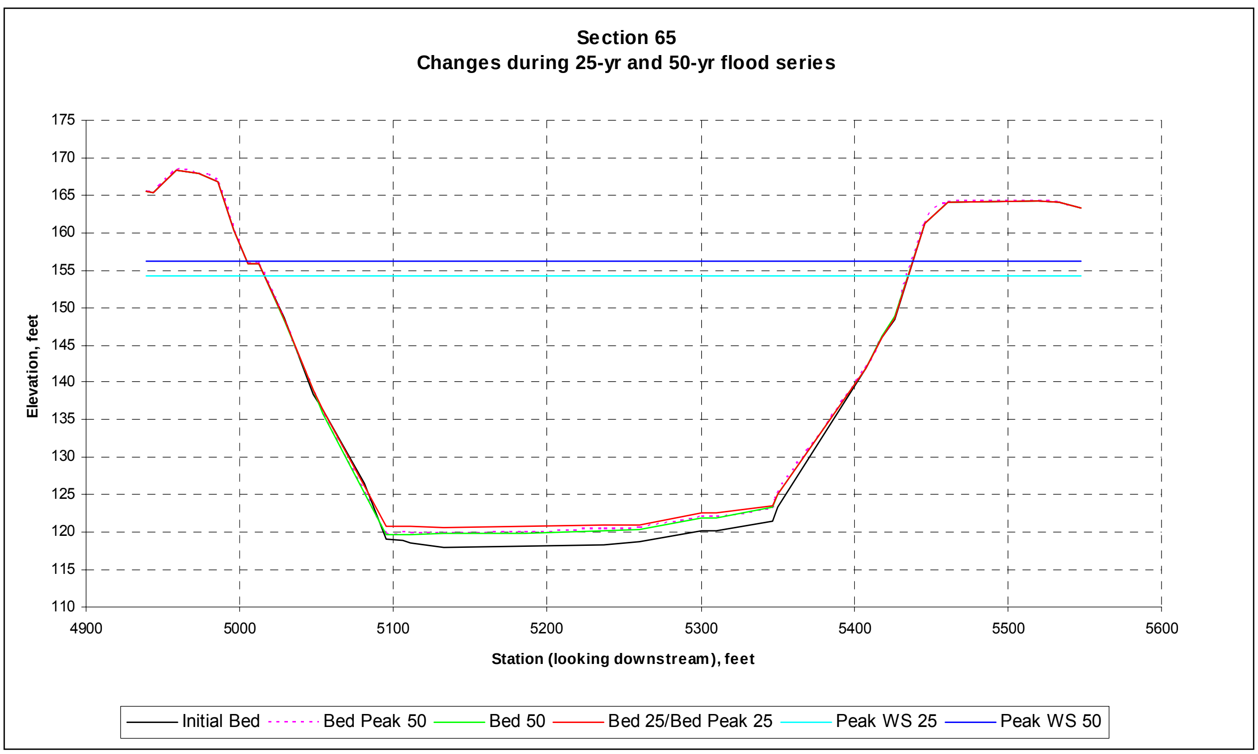

Section 63.9
Changes during 25-yr and 50-yr flood series
Elevation, feet
170
165
160
155
150
145
140
135
130
125
120
115
110
5100
5200
5300
5400
5500
5600
5700
5800
5900
6000
6100
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

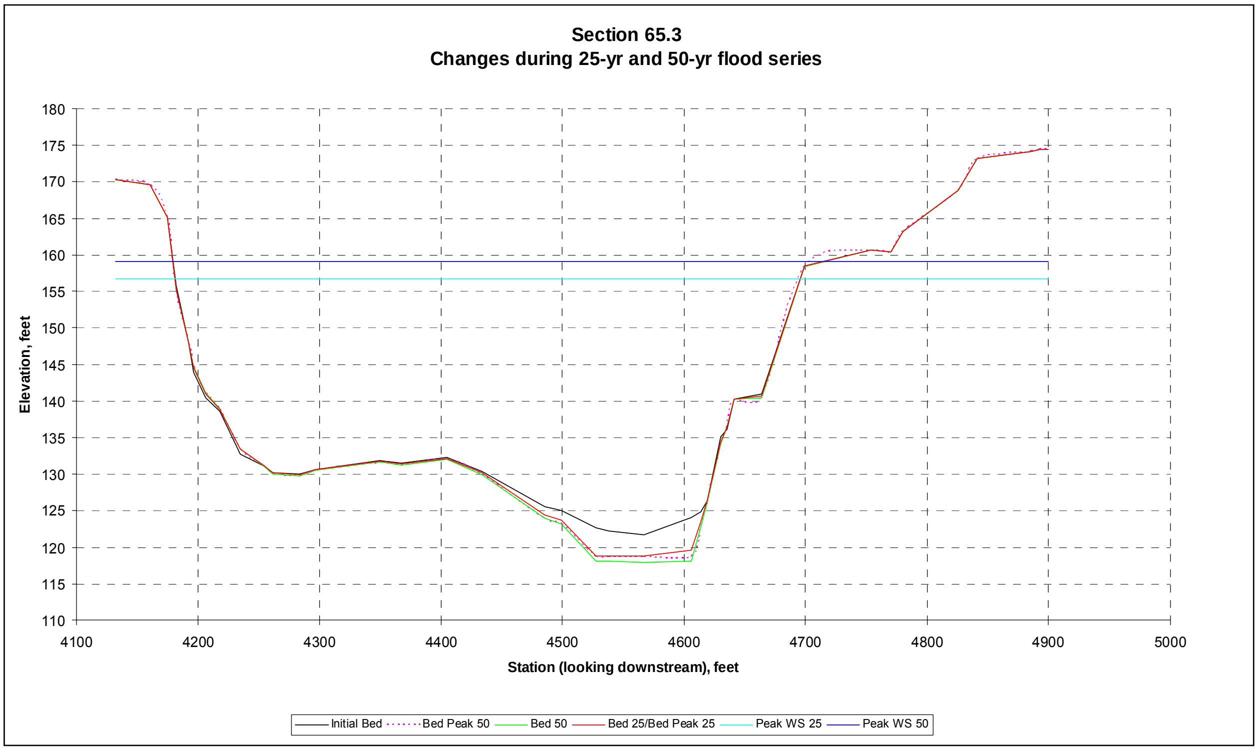

Section 64.2
Changes during 25-yr and 50-yr flood series
Elevation, feet
175
170
165
160
155
150
145
140
135
130
125
120
115
110
5300
5400
5500
5600
5700
5800
5900
6000
6100
6200
6300
6400
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50

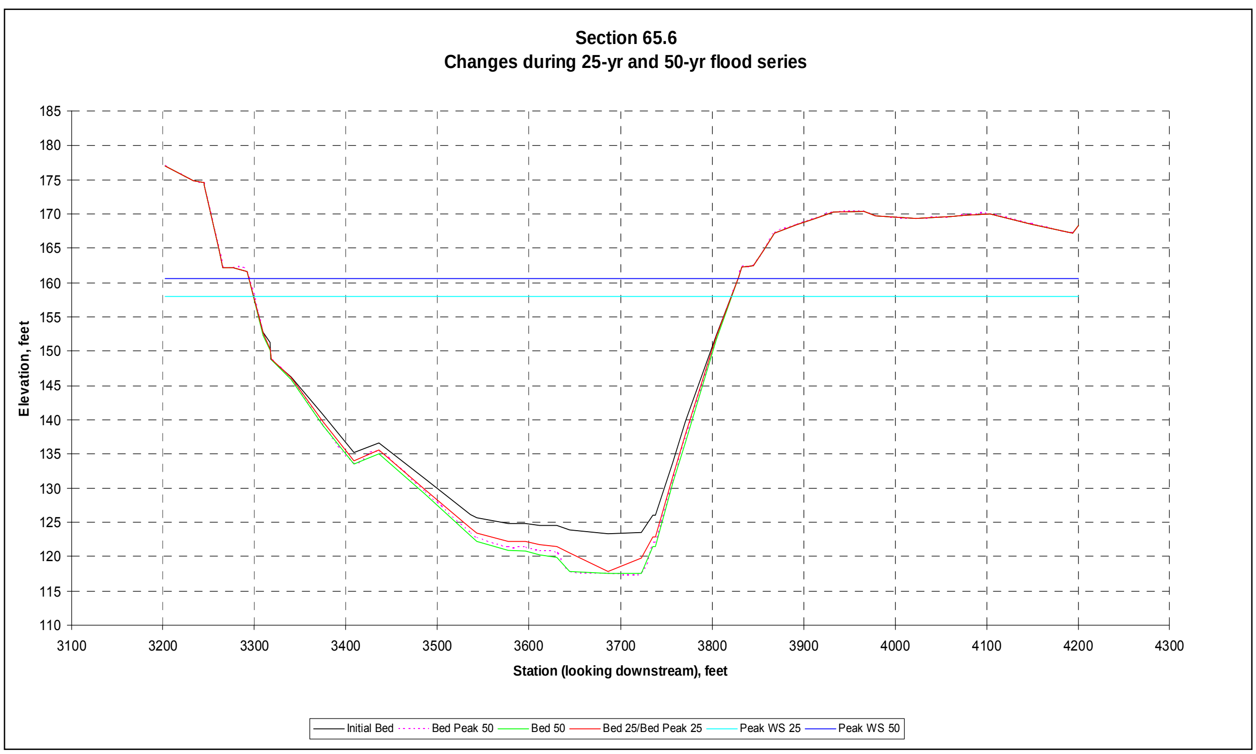

Section 64.4
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50


Section 64.6
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50


Section 64.8
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
180
175
170
165
160
155
150
145
140
135
130
125
120
115
110
5000
5100
5200
5300
5400
5500
5600
5700
5800
5900
6000
6100
6200
6300
6400
6500
6600
6700
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50


Section 65
Changes during 25-yr and 50-yr flood series
Elevation, feet
Station (looking downstream), feet
175
170
165
160
155
150
145
140
135
130
125
120
115
110
4900
5000
5100
5200
5300
5400
5500
5600
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50


Section 65.3
Changes during 25-yr and 50-yr flood series
Elevation, feet
180
175
170
165
160
155
150
145
140
135
130
125
120
115
110
4100
4200
4300
4400
4500
4600
4700
4800
4900
5000
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50


Section 65.6
Changes during 25-yr and 50-yr flood series
Elevation, feet
185
180
175
170
165
160
155
150
145
140
135
130
125
120
115
110
3100
3200
3300
3400
3500
3600
3700
3800
3900
4000
4100
4200
4300
Station (looking downstream), feet
Initial Bed
Bed Peak 50
Bed 50
Bed 25/Bed Peak 25
Peak WS 25
Peak WS 50